USING THE FREEZING INDEX FOR THE OPTIMUM SELECTION OF PAVING ASPHALTS WITH DIFFERENT TEMPERATURE SUSCEPTIBILITIES FOR ANY PAVEMENT SITE

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I. INTRODUCTION

At the CTAA meeting in Quebec City two years ago, the writer presented a paper on this topic (1) but without reference to freezing index, which is the number of degree days that the ambient temperature is below freezing during the year. In the present paper, it will be demonstrated that freezing index is related to the pavement temperature measured at any depth below an asphalt paved surface on the hottest and coldest days in a year. It will also be demonstrated how easy it is by using only a straight edge and several design charts, two by Van der Poel to select for a paving asphalt, the optimum combination of penetration at 77°F and temperature susceptibility for any paving project:

(a) for heavy, medium, and light traffic, that will avoid low temperature transverse pavement cracking in winter, and provide adequate stability for warm weather traffic in summer.

(b) for the design of surface, binder and base course layers.

II. THE ROLE OF FREEZING INDEX

For the paper at Quebec City (1), Figure 1 was included which shows the increase in pavement temperature with increasing pavement depth below the surface during the coldest day of the year, and the decrease in pavement temperature with increasing pavement depth below the pavement surface during the hottest day of the year. However, this information is available for only the two sites at which it was measured.

During the full year in 1965, hourly measurements of pavement temperature at the surface and at each 2-inch depth below the surface in an asphalt pavement 12 inches thick were made by The Asphalt Institute at its headquarters at College Park, Maryland, (Washington, D.C.) (2). During the 2-year period, 1968 and 1969, similar temperature data for asphalt pavements 4 inches and 10 inches thick, were measured at Ste. Anne, Manitoba (east of Winnipeg), in a joint research effort by the Manitoba Department of Transportation and Shell Canada (3). The data obtained during these two investigations have been plotted in Figure 1, with temperature as ordinate on an arithmetic scale, and pavement depth as abscissa on a logarithmic scale.

It must be recognized that the data shown in Figure 1 apply only to the temperature conditions that exist at Washington, D.C. and at Ste. Anne Manitoba, where they were actually measured It would be costly and time consuming to obtain similar data for a large number of sites elsewhere. Therefore, it is necessary to use some other measurement of the temperature of the environment to interpolate and extrapolate the data from the two locations in Figure 1 to asphalt paving sites in general. The writer is suggesting that the freezing index can be employed for this purpose.

Figure 2 is a plot of contours of equal freezing index for the entire continent of North America. Figure 2 has been published by Berg and Johnson (4) of the U.S. Corps of Engineers to provide a chart of design freezing indices, which are higher than the charts of average freezing index normally seen in print. The design freezing index for any paving site in North America can be read from Figure 2, or can be easily calculated from temperature information available at a nearby local airport.

Figure 1 is a semi-log graph. Nevertheless, practically the same information is provided if the same data are plotted on a log-log chart, Figure 3. However, there is a practical problem with a log-log graph, in that to avoid logarithms of the negative temperatures in Figure 1, it is necessary to convert these to temperature on the Rankine scale where 0° Rankine is - 459.7°F (or from the Kelvin temperature scale, where 0° Kelvin = -273.2°C). However, as shown on Figure 3, when the data of Figure 1 are plotted with log °R as the ordinate, versus log pavement depth as abscissa on ordinary 8 1/2 by 11 graph paper, the data are so crowded that accurate readings cannot be made.

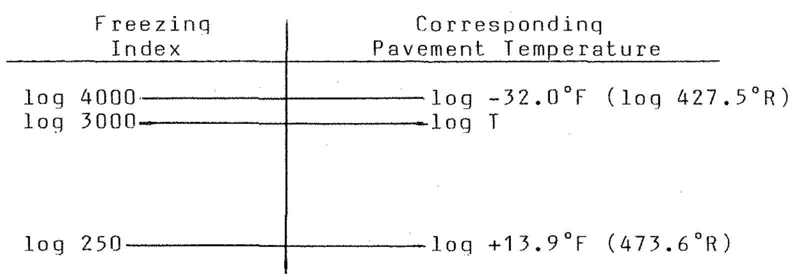
The justification for using the log-log chart of Figure 3, instead of the semi-log graph of Figure 1, is provided by Figures 4(a) and 4(b) which show that in two studies (5), the logarithm of freezing index versus the logarithm of frost depth penetration plots as a straight line. On this basis, it is suggested that the data illustrated in Figure 1 can be represented by a straight line plot of log freezing index versus log pavement temperature for any pavement depth, to provide information on the change of temperature with pavement depth below the surface.

The freezing index for Ste. Anne Manitoba as read from Figure 2 is 4000°F days, and for Washington D.C. is 250°F days. From Figure 1, the minimum pavement temperature for a pavement depth of 2.0 inches at Ste. Anne, Manitoba is -32°F(427.7°R), and the minimum pavement temperature at the same depth at Washington D.C., is +13.9°F(473.6°R). These temperatures provide two points on the straight line graph of log freezing index versus log pavement temperature for a pavement depth of 2 inches, for example, that can be either interpolated or extrapolated to obtain the pavement temperature at a pavement depth of 2-inches for any other freezing index value.

The plot of log freezing index versus log of pavement temperature for a pavement depth of 2-inches is shown in Figure 5.

While Figure 5 pertains to a pavement depth of 2-inches, for a freezing index of 1000°F days the pavement temperatures for pavement depths of both 1-inch and 2-inches are shown. It is obvious that the two points are practically on top of each other, and that trying to illustrate temperature data for all pavement depths form 0 to 20 inches below the surface by means of a chart would lead to considerable inaccuracy when trying to read the temperatures for every freezing index and every pavement depth. Consequently, the relationship between freezing index and pavement temperature for each pavement depth is presented in tabular form, with Table 1 providing this information for minimum pavement temperatures, and Table 2 for maximum pavement temperatures for pavement depths from 0 to 20 inches.

The procedure for calculating the data in Table 1, for any given pavement depth, is illustrated by the following sketch:



Suppose the minimum temperature at a pavement depth of 2.0 inches corresponding to a freezing index of 3000°F days is required.

From Figure 1, the minimum pavement temperature of -32°F (427.5°R) and the corresponding freezing index of 4000°F days, and the minimum pavement temperature of +13.8°F (473.6°R) and the corresponding freezing index of 250 are all known. The minimum pavement temperature T°F corresponding to a freezing index of 3000, for example, is required. This involves solving the following equation for T, the minimum temperature corresponding to a freezing index of 3000:

$$\frac{\log 3000 - \log 250}{\log 4000 - \log 250} = \frac{\log T - \log 473.6}{\log 427.5 - \log 473.6} \qquad (1)$$

For other pavement depths from 0(0.1) to 20 inches, the minimum temperature, T°F, for any corresponding freezing index value is obtained in the same way, resulting in Table 1.

The maximum temperature data at any pavement depth given in Table 2, are obtained on a somewhat similar basis. Lines A and D in Figure 1, result from actual temperature measurements. Lines B and C have been arbitrarily drawn at one-third and two-thirds of the distance from Line A to Line D. From Figure 1, if the minimum temperature for a pavement depth of 1.0 inch is -20°F (-28.9°F), this temperature is 6/7 of the distance from Line D to Line C. At the top of Figure 1, for a pavement depth of 1.0 inch, 6/7 of the distance from Line D to Line C corresponds to a temperature of 113°F (45°C). Consequently, for a pavement depth of 1.0 inch, a maxiuum temperature of 113°F(45°C) corresponds to a minimum temperature of -20°F (28.9°C).

The procedure for calculating the data in Table 2 for any given pavement depth, is similar to that for Table 1.

Suppose the maximum temperature at a pavement depth of 2.0 inches corresponding to a freezing index of 3000°F days is required.

From Figure 1, the maximum temperature of 107.2°F (41.8°C) and the corresponding freezing index of 4000°F days, and the maximum pavement temperature of 127.3°F (52.9°C) for a corresponding freezing index of 250°F days, have been measured and are known. The maximum pavement temperature, T°F (°C), corresponding to a freezing index of 3000°F days is required. This involves solving Equation (1) for T by substituting appropriate values for pavement temperature and freezing index.

Using this procedure for Table 2, the maximum pavement temperature, T°F (°C), for any corresponding freezing index value can be obtained for other pavement depths from 0(0.1) to 20 inches.

it should be pointed out that for regions with tundra or permafrost, the values in Table 1, and Table 2 may not apply.

Limited data for freezing indices and corresponding temperatures, T, for various pavement depths, that have been calculated on the basis of the semi-log relationship shown in Figure 1 between pavement temperature and pavement depth, are given in Tables 3 and 4. However, no further reference to Tables 3 and 4 will be made, and for the reasons given earlier, this paper has been prepared on the assumption of a log-log relationship between freezing index and corresponding pavement temperature versus pavement depth.

A brief review of some data published earlier (1,6) will be presented next as background before demonstrating how Tables 1 and 2 can be applied to the selection of paving asphalts with different temperature susceptibilities for pavements that will be exposed to a wide variety of traffic and temperature environments.

III. BRIEF REVIEW OF EARLIER DATA ON PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY

1. What Is Temperature Susceptibility?

As illustrated by Figure 6, 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. In Figure 6, three paving asphalts, each with the same consistency at 77°F (25°C), but with quite different consistencies above or below 77°F (25°C), are illustrated.

Because Asphalt 3 in Figure 6 has the steepest slope, its consistency changes the most over a given temperature range of the three paving asphalts illustrated, and it is therefore said to have a high temperature susceptibility. It will provide pavements that are harder and therefore more susceptible to low temperature transverse pavement cracking at winter temperatures than the other two paving asphalts, and will also be more fluid at all temperatures above 77°F (25°C). The change in consistency of Asphalt 1, is represented by the flattest slope in Figure 6, and it is said to have low temperature susceptibility. It will provide pavements that are less hard and therefore less susceptible to low temperature transverse pavement cracking at any given winter temperature than Asphalts 2 and 3, and will be less fluid and therefore result in pavements of greater stability at all temperatures above 77°F (25°C) than the other two paving asphalts. The consistency change of Asphalt 2 over the same given temperature range, is indicated by an intermediate slope, and it is therefore said to have intermediate temperature susceptibility Pavements containing Asphalt 2 will have properties intermediate between those made with Asphalts 1 and 3 at temperatures both above and below 77°F (25°C).

2. How Is Paving Asphalt Temperature Susceptibility Measured?

For reasons clearly explained in earlier publications (1,6), the writer measures the temperature susceptibilities of paving asphalts in terms of their pen-vis number (PVN) values. The PVN value for any paving asphalt can be read from Figure 7 as soon as its penetration at 77°F (25°C) and its viscosity at 275°F (135°C) have been measured. By plotting these values as the coordinates of a point on Figure 7, the PVN of the paving asphalt can be easily read approximately by interpolating between the oblique lines representing different PVN Values, or it can be calculated exactly by means of the equations at the top of the chart. Since penetration at 77°F and viscosity in centistokes at 275°F are usually measured during the routine inspection of a sample of paving asphalt, no additonal testing is required.

3. Influence of Paving Asphalt Temperature Susceptibility on Warm Weather Pavement Stability in Tropical or Subtropical Climates With No Frost.

The following illustration pertains to paving asphalt selection in tropical or subtropical climates with no frost. It is included here, because it provides a simple, clear instance of how engineers can use paving asphalt temperature susceptibility to work either for them or against them.

This example of using paving asphalt temperature susceptibility to work against us as engineers, is based on our not uncommon practice of specifying 80/100 (85/100) penetration or 150/200 penetration paving asphalt, etc., for a paving project without the slightest regard for its temperature susceptibility. Figure 8 provides a very simple illustration of this when 80/100 penetration asphalt has been specified for a pavement to carry heavy traffic in a warm region with a maximum pavement temperature of 60°C (140°F) at a pavement depth of 2.0 inches, but where there is never any frost. The shaded area of Figure 10 demonstrates that by merely specifying 80/100 penetration paving asphalt without regard for its temperature susceptibility, an engineer could have a pavement that would develop moduli of stiffness ranging from 11,000 to 18,000 psi under fast 100 km (60 miles) /hr heavy truck traffic if the paving asphalt temperature susceptibility was low (PVN = 0.0 to -0.5), to only from 7000 psi to 12,000 psi if its temperature susceptibility was high. (These modulus of stiffness values are obtained from Van der Poel's nomographs, and their application will be discussed later in the paper). Obviously, a pavement that develops a modulus of stiffness of only 7,000 psi is very much weaker than one that develops a modulus of stiffness of 18,000 psi under equal heavy fast traffic and high temperature conditions. Nevertheless, it has not infrequently happened that pavements made with 80/100 penetration paving asphalt have failed due to low pavement stability because of high temperature susceptibility, much to the surprise and wonderment of engineers who had assumed that adequate pavement stability would be provided if they merely specified 80/100 penetration paving asphalt regardless of its temperature susceptibility.

The hatched area of Figure 8 demonstrates that to develop a modulus of stiffness from 13,500 to 18,000 psi at 60°C (140°F) under fast heavy truck traffic, an engineer should specify:

(a) 80/100 penetration asphalt if its PVN is 0.0
(b) 70/86 penetration asphalt if its PVN is -0.5
(c) 60/76 penetration asphalt if its PVN is -1.0
(d) 50/65 penetration asphalt if its PVN is -1.5

This is an example of how an engineer could make paving asphalt temperature susceptibility work for him rather than against him, particularly when he is faced (as often he is) with only a limited choice of paving asphalt temperature susceptibilities.

4. Selecting Paving Asphalts to Avoid Low Temperature Transverse Pavement Cracking

It should be emphasized that when designing asphalt pavements, Canadian engineers must keep three objectives clearly in mind:

1. How to avoid low temperature transverse pavement cracking in winter.

2. How to provide adequate pavement stability for fast traffic during summer temperatures.

3. How to avoid pavement rutting in warm weather.

Furthermore, each pavement must or should satisfy all three of these objectives.

Figure 9, taken from earlier papers, is presented as the writer's best estimate for selecting paving asphalts of different temperature susceptibilities for the purpose of avoiding, or at least greatly reducing, low temperature transverse pavement cracking during the entire service life of a well designed and properly constructed dense graded asphalt pavement.

Figure 9 shows that for any given low pavement temperature (the temperature at a pavement depth of about 2 inches), for example -20°F (-28.9°C), only the combinations of penetration at 77°F (25°C) and PVN values that lie either on or to the right of the temperature line labelled -20°F (-28.9°C) should be selected for asphalt pavements. Combinations of penetration at 77°F(25°C) and PVN that lie to the left of this line, are too hard, and will result in low temperature transverse cracking in regions where the minimum pavement temperature is -20°F (-28.9°C).

Based on Figure 9, the following are the combinations of penetrations at 77°F (25°C) and PVN values that will just avoid low temperature transverse pavement cracking at a minimum pavement service temperature of -20°F (-28.9°C):

PVN = 0.0 and 165 penetration at 77°F(25°C), or higher (softer)
PVN =-0.5 and 215 penetration at 77°F(25°C), or higher (softer)
PVN =-1.0 and 275 penetration at 77°F(25°C), or higher (softer)
PVN =-1.5 and 345 penetration at 77°f(25°C), or higher (softer)

Each of these combinations of penetration at 77°F (25°C), and PVN represent paving asphalts that will provide dense graded pavements with a modulus of stiffness of 300,000 psi at -20°F (28.9°C) for a loading time of 20,000 seconds, when the pavements are compacted to three per cent air voids.

Similar information can be provided for the other oblique temperature labelled lines in Figure 9.

To facilitate the determination of combinations of corresponding values for PVN and penetration at 77°F (25°C) that will just avoid low temperature transverse pavement cracking at minimum pavement temperatures between those shown by the temperature labelled oblique lines in Figure 9, the data in Figure 9 have been rearranged to provide Figure 10, in which the ordinate axis provides a continous minimum temperature scale.

When engineers see the rather high penetrations at 77°F (25°C) for paving asphalts of high temperature susceptibility required to avoid low temperature transverse pavement cracking, some will be wondering about the stability of pavements containing these soft paving asphalts for warm weather traffic. This item will be considered next.

5. Relationship Between Paving Asphalt Temperature Susceptibility and Traffic Volume

The Ontario Ministry of Transportation and Communications, The Asphalt Institute, and probably other agencies divide traffic volume into three categories, heavy, medium and light. These organizations also require the highest minimum stability for heavy traffic, a lower minimum stability for medium traffic, and the lowest minimum stability for light traffic. Table 5 indicates that Ontario specifies minimum Marshall stabilities at 140°F (60°C) of 8900 Newtons (2000-lb) for heavy traffic, 6700 N (1500-lb) for medium traffic, and 4400 N(1000-lb) for light traffic. In this paper, pavement stability is usually expressed as modulis of stiffness in psi (kPa or MPa), that are taken from Van der Poel's nomographs. As shown on Table 5, as a rough rule of thumb, based on observations of pavement performance in the Philippines, Thailand and other tropical countries, it appears that a minimum modulus of stiffness in psi at the maximum pavement temperature anticipated for a pavement project, that is 10 times Ontario's minimum Marshall stability requirement at 140°F will provide a reasonable criterion for warm weather pavement stability.

The specifications of many highway, street and airport agencies bar (exclude) all paving asphalts except those of low or relatively low temperature susceptibilities from all traffic categories. Figure 11 demonstrates that this is a needless engineering requirement, that for many roads, streets and airport runways carrying only medium or light traffic can be unnecessarily costly and wasteful.

This section of the paper pertains to the selection of paving asphalts with a wide range of temperature susceptibilities (PVN values) for heavy, medium and light traffic. For this particular example, illustrated by Figure 11, the only asphalts to be considered are those on or to the right of the line labelled -10°F (-23.3°C) in Figure 9, that provide pavements that will avoid low temperature transverse pavement cracking at this minimum pavement service temperature.

Across the top of Figure 11, it is shown that heavy traffic should be assigned to pavements containing the hardest asphalts (lowest penetrations of 130 to 160 at 77°f(25°C)) with the highest moduli of stiffness from 22,000 to 31,500 psi, medium traffic to pavements containing somewhat softer paving asphalts (higher penetrations at 77°f (25°C) from 160 to 200) that furnish lower moduli of stiffness values from 17,000 to 22,000 psi, and light traffic to pavements incorporating still softer paving asphalts (higher penetrations at 77°F (25°C) from 200 to 245) that provide still lower pavement stabilities indicated by pavement moduli of stiffness ranging from 13,000 to 17,000 psi.

In every case, these pavement moduli of stiffness values for heavy, medium, and light traffic categories are for truck traffic travelling at 100 km (60 miles) per hour when the maximum pavement temperature at a pavement depth of about 2.0 inches is 47.2°C (117°F) which correlates with a minimum pavement temperature of (-10°F) (-23.3°C). This is in agreement with the principle adopted by many organizations that for lower and lower traffic volumes lower and lower pavement stabilities are adequate.

As shown on the left side of Figure 11, heavy traffic should be transported on pavements containing asphalts of lowest temperature susceptibility, PVN = 0.0 to -0.5, because these provide the highest pavement modulus of stiffness values, 22,000 to 31,500 psi at 117°F (47.2°C). Medium traffic should be carried on pavements containing asphalts of medium temperature susceptibility, PVN = -0.5 to -1.0, since these furnish somewhat smaller moduli of stiffness, 17,000 to 22,000 psi. Light traffic should be associated with pavements containign paving asphalts of high temperature susceptibility, PVN = -1.0 to -1.5, because these develop still smaller moduli of stiffness, 13,000 to 17,000 psi.

When selected on this basis, it is evident from the stippled areas in Figure 11, that for pavements to carry traffic at a maximum pavement temperature of 117°F (47.2°C) in a region where the corresponding minimum pavement temperature is -10°°F (-23.3°C), the hardest paving asphalts of lowest temperature susceptibility, PVN = 0.0 to -0.5, and of the lowest penetration at 77°F (25°C) of 130 to 165, should be selected for pavements to carry heavy traffic, slightly softer asphalts of medium temperature susceptibility, PVN = -0.5 to -1.0, and of somewhat higher penetration at 77°F (25°C), 165 to 200, should be selected for pavements for medium traffic, while yet softer paving asphalts of high temperature susceptibility, PVN = -1.0 to -1.5, and with still higher penetrations at 77°F (25°C), 200 to 240, should be selected for pavements for light traffic.

While Figure 11 pertains to the selection of paving asphalts that avoid low temperature transverse pavement at a minimum winter pavement temperature of -10°F (-23.3°C), and that will provide adequate pavement stability for fast traffic at the corresponding maximum summer temperature of 117°F (42.7°C), similar information can be easily determined for regions with other corresponding combinations of maximum summer and minimum winter pavement temperatures.

6. Selecting Paving Asphalts for Surface, Binder and Base Course Layers

Figure 1 indicates that for the coldest day in winter, pavement temperatures become increasingly and substantially higher with increasing depth below the surface, while for the hottest day in summer, pavement temperatures become increasingly and substantially lower with increasing pavement depth below the surface.

In the paper presented two years ago (1), it was shown that recognition of this fact in regions where paving asphalts of low temperature susceptibility used for surface courses for heavy traffic are scarce, makes it possible to consider paving asphalts of higher temperature susceptibility for the binder and base course layers beneath the surface course.

Based on the temperature data for pavement depths below the surface illustrated in Figure 1, the stability data in the extreme right hand column of Table 6 provide pavement modulus of stiffness values for a 6-inch pavement structure consisting of a 2-inch surface course, a 2-inch binder course and a 2-inch base course, that are developed under fast traffic on what is assumed to be the hottest day in summer for the particular paving site, 113°F(45°C) at a pavement depth of 1-inch.

The average minimum pavement temperature for the 2-inch surface course is approximated by the pavement temperature at a pavement depth of 1-inch, for the 2-inch binder course by the pavement temperature at a pavement depth of 3-inches, and for the 2-inch base course by the pavement temperature at a pavement depth of 5-inches.

Figure 1 shows that when the pavement temperature at a pavement depth of 1-inch is -20°C(-28.9°C), the pavement temperature at a pavement depth of 3-inches is -14°F(-25°C), and the pavement temperature at a pavement depth of 5 inches is -7°F(-21.7°C). The corresponding maximum temperature as indicated by Figure 1, at a pavement depth of 1-inch is 113°F(45°C), at a pavement depth of 3-inches is 105°F(40.6°C), and at a pavement depth of 5-inches is 95°F(35°C).

These data demonstrate that because of the increasingly higher pavement temperatures with increasing depth below the surface in winter, increasingly harder paving asphalts can be used for the binder and base course layers at pavement depths of 3-inches and 5-inches that will still avoid low temperature transverse pavement cracking. The increasingly harder asphalts that can be used at these increasing pavement depths, also develop increasingly higher pavement stabilities under fast traffic at summer temperatures of 113°F(45°C), 105°F (40.6°C) and 95°C (35°C), respectively, as shown in the right hand column of Table 6.

Based on the average pavement modulus of stiffness values taken from the right hand column of Table 6 for low, medium and high paving asphalt temperature susceptibilities, Figure 12 indicates the influence on pavement modulus of stiffness values from selecting paving asphalts of different temperature susceptibilities for surface, binder and base course layers for heavy, medium and light traffic.

To conserve space in Figure 12, modulus of stiffness values for pavements containing paving asphalts of low temperature susceptibility, PVN = 0.0 to -0.5, carry an accompanying symbol A. Modulus of stiffness values for pavements containing paving asphalts of medium temperature susceptibility, PVN = -0.5 to -1.0, have an associated symbol B, while the symbol C is attached to modulus of stiffness values for pavements made with paving asphalts of high temperature susceptibility, PVN = -1.0 to -1.5.

The following principles of design are illustrated by Figure 12 for an asphalt pavement structure consisting of three 2-inch layers of surface, binder and base course, containing paving asphalts of low, medium, and high temperature susceptibility, and for heavy, medium and light traffic:

(a) The surface course layer for heavy traffic should contain paving asphalt of low temperature susceptibility, the surface course for medium traffic can incorporate a paving asphalt of medium temperature susceptibility, while for light traffic, the surface course may contain paving asphalt of high temperature susceptibility. However, if paving asphalt of low temperature susceptibility is readily available, it could be employed for the surface course for both medium and light traffic.

(b) For the underlying binder and base course layers, as shown by Figure 12, when paving asphalts of low temperature susceptiblity are scarce, paving asphalts of medium and high temperature susceptibility can be used, even though they develop under fast summer traffic, a pavement modulus of stiffness that can range from slightly to substantially less than that developed by a paving asphalt of low temperature susceptibility.

It should be obvious that the same principles for the selection of paving asphalts of different temperature susceptibilities and for heavy, medium and light traffic, apply to other combinations of thicknesses of surface, binder and base course layers than those illustrated by Table 6 and Figure 12.

IV. USING THE FREEZING INDEX FOR THE OPTIMUM SELECTION OF PAVING ASPHALTS WITH DIFFERENT TEMPERATURE SUSCEPTIBILITIES FOR VARIOUS PAVING SITES

For Table 6 and Figure 12, a minimum pavement temperature of -20°F(-28.9°C) and corresponding maximum pavement temperature of 113°F(45°C) at a pavement depth of 2 inches were arbitrarily selected from Figure 1 for purposes of illustration. However, the corresponding minimum and maximum pavement temperatures to be assigned to any proposed paving site are normally unknown, and would have to be either measured at considerable cost and effort, or estimated.

It is to facilitate the selection of the minimum and maximum pavement temperatures at any pavement depth at any paving site, that Tables 1 and 2 have been prepared, where freezing index is employed as a measure of the temperature of any environment.

1. Selecting the Paving Asphalt for a Single Layer Surface Course

It will now be shown how easy it is, employing only a straight edge, to use the freezing indices in Tables 1 and 2, and several related charts, to select the optimum paving asphalt in terms of its penetration at 77°F(25°C) and its PVN value for any paving site.

Suppose a one-course asphalt pavement 3-inches thick is to be constructed as a single layer on a prepared granular base.

Suppose further that the following limiting conditions are associated with the pavement design and with the paving site:

(a) A freezing index of 1500°F days
(b) A paving asphalt with a PVN of -0.2 is available
(c) As a guide to establishing whether the pavement should be designed for heavy, medium, or light traffic:
    heavy traffic requires a PVN from 0.0 to -0.5
    medium traffic requires a PVN from -0.5 to -1.0
    light traffic requires a PVN from -1.0 to -1.5
(d) A traffic survey indicates that the pavement should be designed for heavy traffic.

Based on these limitations for the paving site, the following steps are involved in the selection of the paving asphalt for the paving mixture to be used. Only a straight edge and several simple charts are required.

Step 1. Since the pavement is to be constructed as a single layer 3-inches thick, the average minimum temperature of the surface layer will be approximately the minimum pavement temperature at a pavement depth of 1.5 inches.

Step 2. Enter Table 1 at a freezing index of 1500°F days with a straight edge. Proceed horizontally to a pavement thickness of 1.5 inches and read off the temperature, -16.6°F(-27°C).

Step 3. With a straight edge, enter the ordinate axis of Figure 10 at a temperature of -16.2°F, proceed horizontally to a PVN of -0.2, and then vertically downward to intersect the abscissa. This point of intersection occurs at a penetration at 77°F of 165.

Step 4. Referring next to Figure 7, place a straight edge at 165 penetration at 77°F(25°C) on the abscissa, proceed vertically upward to a PVN of -0.2, and then horizontally to the ordinate axis where the corresponding viscosity at 275°F can be read, which is very nearly 280 centistokes.

This is the answer to the grade of paving asphalt to be selected, a penetration of 165 at 77°F and a PVN of -0.2 or a viscosity at 275°F of 280 centistokes, since it was shown in earlier papers (1,6) that if the paving asphalt for a pavement satisfies the requirements for eliminating or greatly reducing low temperature transverse pavement cracking, it will at the same time provide a well designed and constructed asphalt pavement with adequate stability for warm weather traffic.

If the paving site engineer disagrees with this and selects a harder asphalt (lower penetration at 77°F(25°C)), he should know that he will pay a price for his decision in terms of low temperature transverse pavement cracking.

2. Selecting the Paving Asphalts for a Two Course Pavement

The simple calculations required to select the paving asphalts for a 2-inch surface course on a 4-inch base course will next be illustrated. The limitations associated with pavement design at this site are as follows:

(a) A freezing index of 3000°F days
(b) Paving asphalt with a PVN of -0.4 is relatively scarce but will be used for the surface course.
(c) Paving asphalt with a PVN of -0.7 is readily available and will be used for the base course.
(d) A traffic survey indicates that the pavement should be designed for heavy traffic.

First, the steps in the selection of the paving asphalt for the 2-inch surface course will be illustrated:

Step 1. Since the surface layer is to be 2 inches thick, the average minimum temperature of the 2-inch surface course will be the pavement temperature at a pavement depth of one inch.

Step 2. Enter Table 1 at a freezing index of 3000°F days with a straight edge. Proceed horizontally to a pavement depth of one inch, and read off the pavement temperature, which is -27.8°F(-33.2°C)

Step 3. With a straight edge, enter the ordinate axis of Figure 10 at a temperature of -27.8°F, proceed horizontally to a PVN of -0.4, and then vertically downward to intersect the abscissa. This point of intersection occurs at a penetration at 77°F of 265.

Step 4. Referring next to Figure 7, place a straight edge at 265 penetration at 77°F(25°C) on the abscissa, proceed vertically upward to a PVN of -0.4, and then horizontally to intersect the ordinate axis. From this point of intersection, a viscosity of 170 centistokes can be read.

Next for the selection of the paving asphalt for the 4-inch base course.

Step 1. Since the base course layer is 4-inches thick, the average pavement temperature for the 4-inch base course will occur at a pavement depth of 4 inches.

Step 2. Enter Table 1 at a freezing index of 3000°F days with a straight edge. Proceed horizontally to a pavement depth of 4 inches and read off the minimum pavement temperature, which is -17.1°F(-27.3°C).

Step 3. With a straight edge, enter the ordinate axis of Figure 10 at a temperature of -17.1°F, proceed horizontally to a PVN of -0.7, then vertically downward to intersect the abscissa. This point of intersection occurs at a penetration at 77°F(25°C) of 225.

Step 4. Referring next to Figure 7, place a straight edge on the abscissa at a penetration of 225 at 77°f, proceed vertically upward to a PVN of -0.7, and then horizontally to intersect the ordinate axis. From this point of intersection a viscosity at 275°F of 170 centistokes can be read.

To summarize the selection of paving asphalts for this 6-inch pavement. For the 2-inch surface course, the paving asphalt should have a penetration at 77°F(25°C) of 265 with a corresponding PVN of -0.4 or with a viscosity at 275°F(135°C) of 170 centistokes, Figure 7. For the 4-inch base course, the paving asphalt should have a penetration at 77°F(25°C) of 225 with a corresponding PVN of -0.7 or with a viscosity at 275°F(135°C) of 170 centistokes, Figure 7.

3. Pavement Moduli of Stiffness at Maximum Service Temperatures

While the simple procedure that has been presented is all that is necessary for the selection of paving asphalts for any paving project, some engineers may wish to determine for themselves what corresponding pavement modulus of stiffness would be developed by warm weather traffic at the maximum pavement temperature anticipated at any paving site. This information can also be very easily determined by consulting only three Van der Poel charts in succession, and employing no more complicated equipment than a straight edge.

This procedure will be illustrated with data from the first sample calculation presented above, which indicated that a paving asphalt of 165 penetration at 77°F, with a PVN of -0.2 or with a viscosity at 275°F of approximately 280 centistokes was required.

Step 1. From Table 2, the maximum temperature to be expected at a pavement depth of 1.5 inches for a freezing index of 1500°F days is 114.9°F(46.1°C)

Step 2. Employing Figure 13, the base temperature for a paving asphalt of 165 penetration at 77°F with a PVN of -0.2 is required. It can be obtained by placing a straight edge on the right ordinate at a penetration of 165, and on the oblique line at a PVN of -0.2, and reading its point of intersection on the left ordinate, which is 16°C. Adding the temperature from the right ordinate used for the penetration test, 25°C, gives the base temperature of 16 + 25 = 41°C. In Figure 14, service temperatures are expressed above or below this base temperature. Since in this case, the service temperature is 46.1°C, it is 46.1 - 41 = 5.1°C above the base temperature.

Step 3. Next we need the modulus of stiffness of the paving asphalt, which can be derived from Figure 14, one of Van der Poel's nomographs (7). Figure 14 has several horizontal scales. At the bottom of the figure for loading time, in the middle of the page for temperature, and near the top for PVN values. A heavy truck travelling at 100 km (60 miles) per hour provides a loading time of 0.01 second for a point on a pavement. Placing a straight edge at a loading time of 0.01 second, and on the temperature scale at 5.1°C above the base temperature, and reading off its point of intersection with a PVN = -0.2, gives a modulus of stiffness for the paving asphalt of 1.3 kg/cm^2 = 1.3 x 14.2 = 18.5 psi.

Step 4. Finally from Figure 15, which is another of Van der Poel's nomographs (8), for the same conditions of loading time and service temperature, the modulus of stiffness of a dense graded paving mixture that contains this paving asphalt, and has been compacted to three per cent air voids, is required.

Using a straight edge, enter the abscissa of Figure 15 at the paving asphalt modulus of stiffness of 18.5 psi, proceed vertically upward to the curve, C_V = 0.88, (which represents a well designed dense graded paving mixture made with aggregate with a nominal maximum particle size of 5/8 inch, and that has been compacted to 3 per cent air voids), and then horizontally to the left ordinate which it intersects at a pavement modulus of stiffness of 29,000 psi.

Using the same procedure for the second sample calculation above, the pavement modulus of stiffness for the 2-inch surface course layer with a nominal maximum aggregate particle size of 5/8 inch (C_V=0.88), and containing paving asphalt of 265 penetration at 77°F with a PVN of -0.4, is 27,000 psi, and the pavement modulus of stiffness of the 4-inch asphalt base course with a nominal maximum aggregate particle size of 3/4 inch, (C_V=0.89), and containing a paving asphalt of 225 penetration at 77°F with a PVN of -0.7, is 50,000 psi.

It was indicated earlier that for thin asphalt pavements, or for surface course layers, to carry heavy traffic a minimum warm weather pavement modulus of stiffness of 20,000 psi would be required for the warmest pavement temperature on the hottest day. This pavement modulus of stiffness is exceeded substantially by the 3.0 inch pavement and by the 2-inch surface course employed for each of the above sample calculations.

V. GENERAL COMMENTS

1. It has been estimated (9) that in North America, paving asphalts are presently made from some 600 crude oils or crude oil blends. The property of a paving asphalt that is most greatly affected by this wide variety of crude oil sources is its temperature susceptibility.

2. At present neither AASHTO nor ASTM specifications for paving asphalts contain a temperature susceptibility item. However, the temperature susceptibility of paving asphalts is now receiving so much attention, that specifications at least similar to that illustrated in Figure 16 can be expected, in which paving asphalts are divided into three groups, Groups A, B and C, in terms of their temperature susceptibilities. Group A would include paving asphalts of low temperature susceptibility, Group B, paving asphalts of medium temperature susceptibility, and Group C, paving asphalts of high temperature susceptibility.

3. How would such a specification affect the asphalt supplier, the asphalt user, and the paving contractor?

4. First, how would it affect the asphalt supplier?

(a) At present asphalt suppliers are largely at the mercy, partly of the spot market for crude oils for the refinery, unless they have their own crude oil sources, but primarily of the huge market for petroleum distillates, and they have to sell whatever asphalt the crude oil provides.

(b) Some 15 years ago, and earlier, asphalts from Venezuelan crude oils were available in Eastern Canada. The asphalts from Venezuelan crude oils were normally of low temperature susceptibility and would be included in Group A in Figure 16.

(c) At present in Eastern Canada, which is used only as an example, paving asphalts from every supplier are at the boundary between Group B and Group C asphalts. That is, they are almost on the boundary between medium and high temperature susceptibility. When these asphalts are used in pavements, if they are hard enough (low penetration at 77°F) to provide adequate pavement stability for warm weather traffic, they are so hard that they will inevitably result in severe low temperature transverse pavement cracking. For proof of this just look around you when driving. The bumpety-bump provided by the low temperature transverse pavement cracking in some asphalt pavements is as bad or worse than that which we like to associate with portland cement concrete pavements.

(d) A specification like that illustrated by Figure 16, does not necessarily mean that suppliers will need a great multitude of storage tanks to supply the various paving grades that may be required in any marketing area. Even if a supplier wishes to provide paving grades in all three groups, Groups A, B and C, he requires only 6 storage tanks, 2 for Group A, 2 for Group B and 2 for Group C, one tank for the hardest grade and one tank for the softest grade for each paving asphalt group. All other grades required in any group would be made by blending asphalts from these two tanks. The technology for this type of blending has been available for many years, and has been greatly improved recently.

(e) A major criticism of the specification illustrated in Figure 16, is the existence of gap grading. Consequently, by using the method for paving asphalt selection described in this paper, an engineer would quite often find that his optimum selection of paving asphalt for some paving project would fall into one of the gaps between grades.

(f) Ultimately, therefore, a continuous specification like that illustrated in Figure 17 can be anticipated in which no gaps occur over the entire range between the hardest and softest paving grades required. If to provide a paving asphalt within one or more of the three Groups A, B or C, a supplier is prepared to blend from one tank holding the hardest grade and from another containing the softest grade in order to provide one of the gap graded asphalts, why should he not be prepared to supply any specified asphalt between the extremities of the specification? For a continuous specification like that of Figure 17, it would be only necessary to require that the penetration of the asphalt to be supplied must be within that specified ± so many points for tolerance, e.g. a penetration of 187 ± 15.

(g) In view of the relatively high temperature susceptibility of the paving asphalts presently available in Eastern Canada, and their negative effect on cold weather pavement performance particularly, can anything be done to improve the temperature susceptibility of paving asphalts?

(h) Recently, the President of McAsphalt Industries Limited, Mr. John J. Carrick, decided to add a polymer chemist, Dr. Azizian, to our staff. Already Dr. Azizian has demonstrated that the addition of one per cent of a certain polymer to a paving asphalt near the boundary between Group B and Group C asphalts has improved its temperature susceptibility to Group A, with a further improvement by adding 1.5 per cent of this polymer, Figure 18.

(i) Improving the temperature susceptibility of paving asphalts by the addition of polymers is only in its infancy, but it holds promise of changing the asphalt supply situation away from, "sorry, you have to take what is available, there is no other choice."

(j) The addition of polymers to improve the temperature susceptibility and other properties of paving asphalt, would for the first time change the current asphalt market from one controlled by the suppliers to one controlled by the users.

3. How will recognition of the important role of paving asphalt temperature susceptibility affect the asphalt user?

(a) For the first time, an engineer would be able to employ paving asphalts in pavement layers where they would be most useful, Group A asphalts for heavy traffic, Group B asphalts for medium traffic and Group C asphalts for light traffic. Also for heavy traffic in regions where Group A asphalts are scarce, they would be restricted to use in the surface course, while Group B and sometimes Group C asphalts would be specified for binder and base course layers.

(b) As already indicated by Item (h) in the previous section, if improving the temperature susceptibility of paving asphalts by polymers turns out to be attractive on a cost/benefit basis, the control of the asphalt market would change from the suppliers to the users. For the first time, if an engineer decides that asphalt of a certain penetration at 77°F and with a certain temperature susceptibility is optimum for a certain paving project, asphalt suppliers could no longer tell him that that particular paving asphalt was not available. It could easily be improved adding a proper polymer.

(c) It should be added that asphalts from medium to high temperature susceptibility are ordinarily plentiful, and without any treatment (additive), when properly chosen, they are satisfactory binders for pavements for medium and light traffic. In many regions, paving asphalts of low temperature susceptibility, that are required for heavy traffic, are scarce or not available. It is for these areas in particular, that the addition of an effective polymer to a Group B or Group C asphalt to improve its temperature susceptibility to Group A, provides a most attractive and most useful market for polymer modified asphalts.

4. How will recognition of the important role of paving asphalt temperature susceptibility affect the contractor?

(a) It is not expected that the use of polymer modified asphalts will substantially affect the mixing temperature, the spreading, or the compaction of paving mixtures.

(b) A contractor would require more storage capacity for additional asphalt grades at his mixing plant.

(c) Rather than providing additional permanent or semi-permanent asphalt storage tanks at his mixing plant, a contractor may prefer to operate largely from mobile storage capacity.

(d) If they are to satisfy specifications, all contractors would be equally affected, and therefore no contractor would ordinarily have a cost advantage.

Summary

1. The freezing index is a readily available and widely used indirect measure of the minimum temperature at any paving site.

2. A semi-log or log-log relationship has been established between the pavement temperature on the coldest and hottest days of the year, and the pavement depth below the surface,at Washington, D.C., and at Ste. Anne, Manitoba. Accumulating these data is a costly and time consuming task.

3. This relationship can be generalized by substituting freezing index for the lowest pavement temperature, and for the highest pavement temperature at these two locations. Therefore, a log-log relationship between freezing index and pavement temperature has been developed for any depth of pavement below the pavement surface.

4. This relationship is employed for the selection of the optimum paving asphalt in terms of the combination of its penetration at 77°F and its corresponding temperature susceptibility for the conditions of traffic and temperature associated with each pavement site.

5. Paving asphalt temperature susceptibility and its measurement by pen-vis number (PVN), are reviewed.

6. For tropical and subtropical climates without frost, it is demonstrated that the penetration at 77°F specified for a paving asphalt should decrease as its temperature susceptibility increases.

8. It is pointed out that in Canada and also in the Northern U.S.A, particularly, the same pavement should be designed to avoid low temperature transverse pavement cracking in winter and to provide adequate stability for fast truck traffic in summer. All information in this paper is presented with these two basic requirements in mind.

9. A chart is provided for the selection of paving asphalts in terms of penetration at 77°F(25°C) and temperature susceptibility to avoid low termperature transverse pavement cracking at a range of lowest winter temperatures.

10. For cold climates, it is shown that paving asphalts of low temperature susceptibility should be used for surface courses or for thin asphalt pavements that are to carry heavy traffic, while paving asphalts of medium and high temperature susceptibility can be used for medium and light traffic.

11. For pavements for heavy traffic, it is indicated that when paving asphalts of low temperature susceptibility are in short supply, they should be reserved for surface courses, and that paving asphalts of medium and sometimes high temperature susceptibility can be used for the underlying binder and base course layers.

12. In the general comments section, it is demonstrated how recognition of the importance of paving asphalt temperature susceptibility would affect the asphalt supplier, the asphalt user, and the paving contractor.

13. In the general comments section, it is also shown how the addition of polymers to asphalt, promises for the first time to turn what has always been an asphalt suppliers' market into an asphalt users' market.

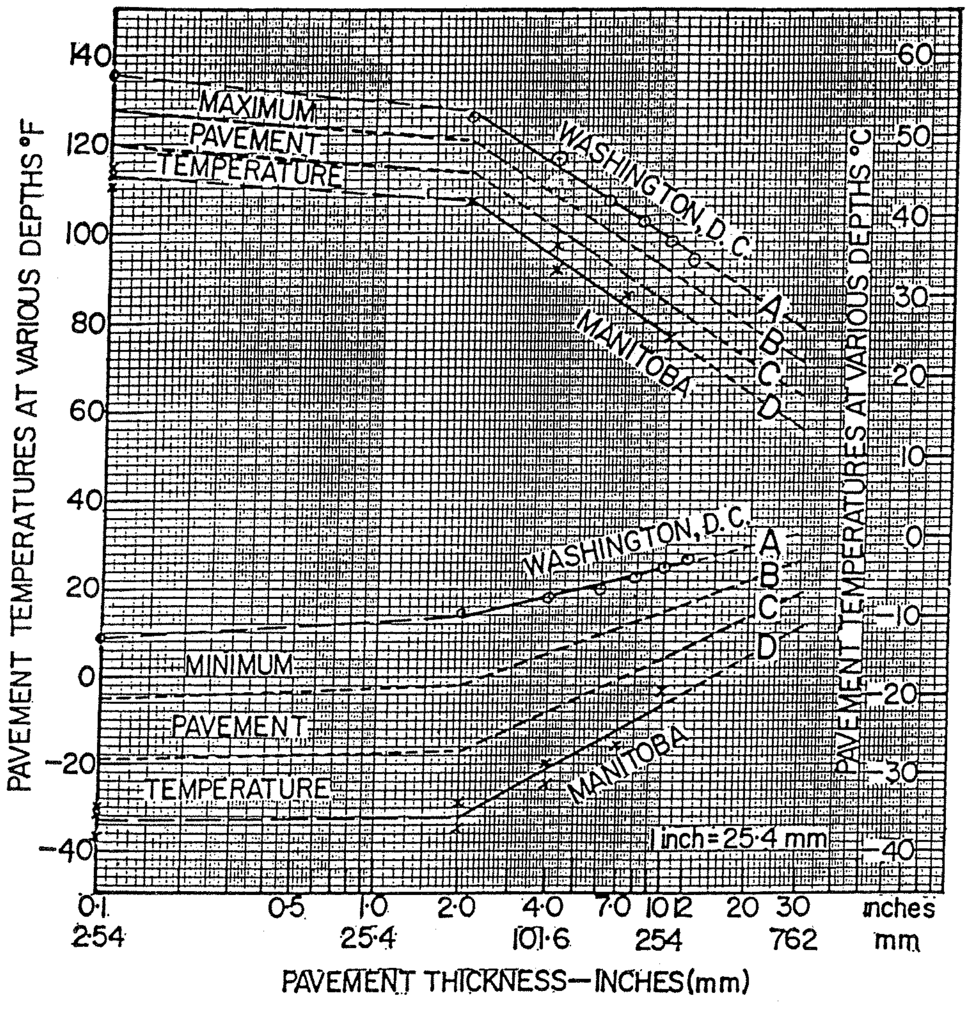


FIGURE 1 CHANGE IN ANNUAL MAXIMUM AND MINIMUM TEMPERATURES WITH PAVEMENT DEPTH AT STE. ANNE, MANITOBA AND AT WASHINGTON, D.C.

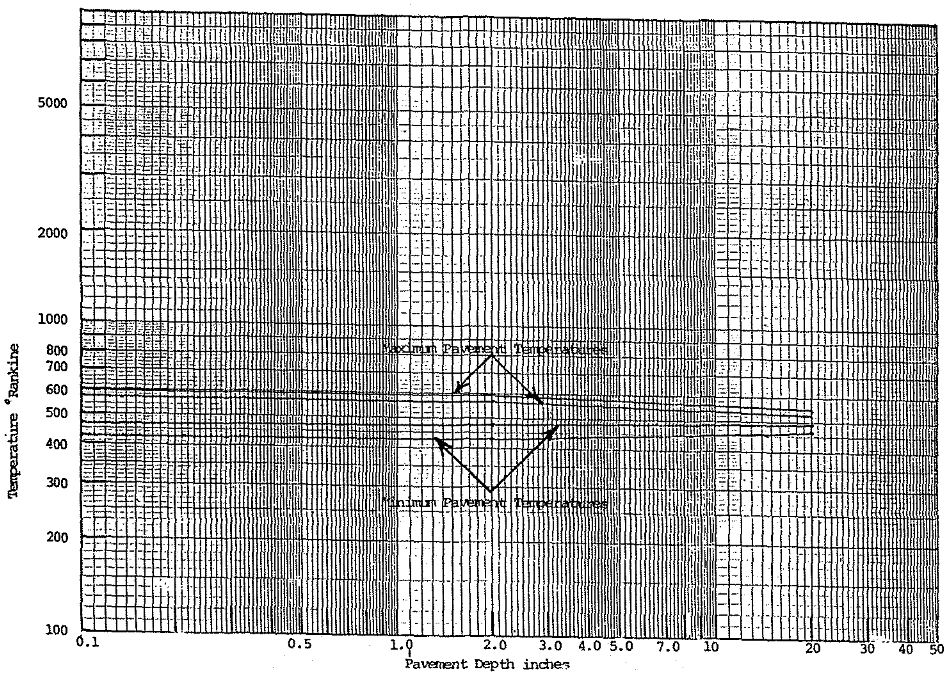


Figure 3 Change in Logarithm of Annual Minimum and Maximum Pavement Temperatures, °R, With Logarithm of Pavement Depth in inches.

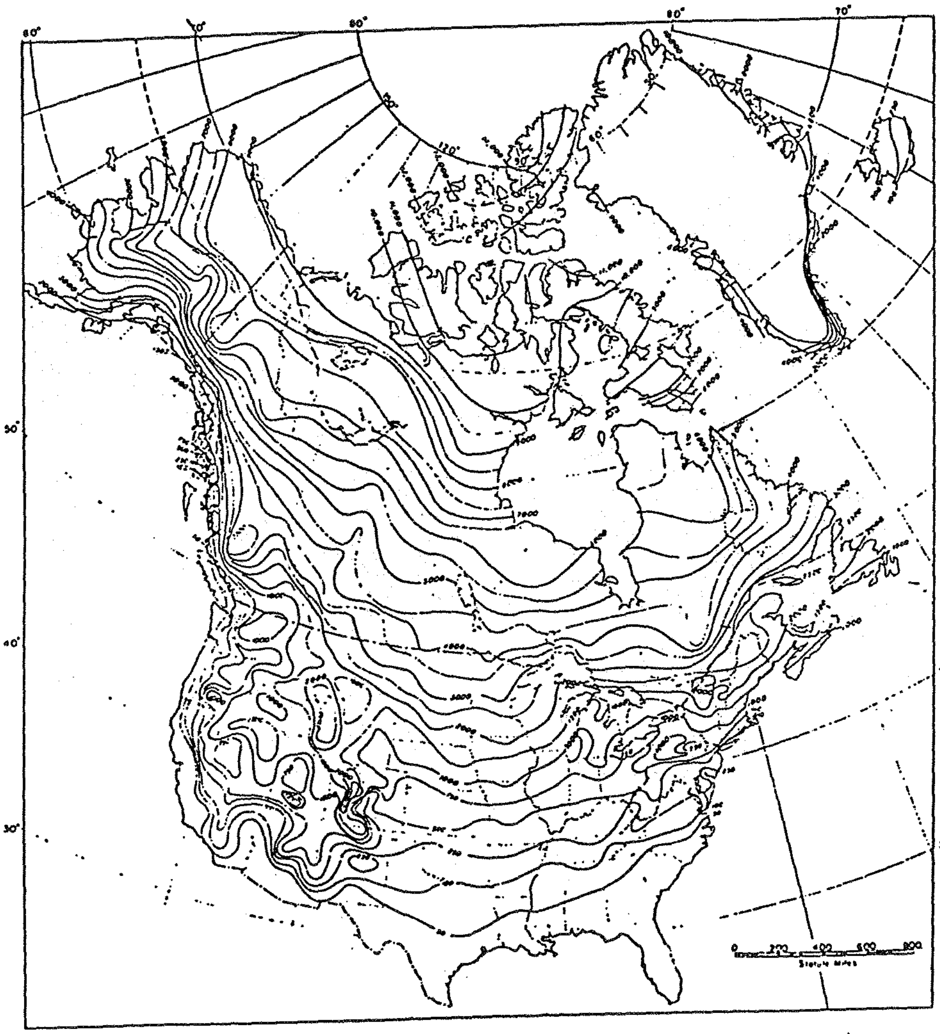


Figure 2 **Distribution of design air freezing indices in North America.** (Courtesy U.S. Corps of Engineers)

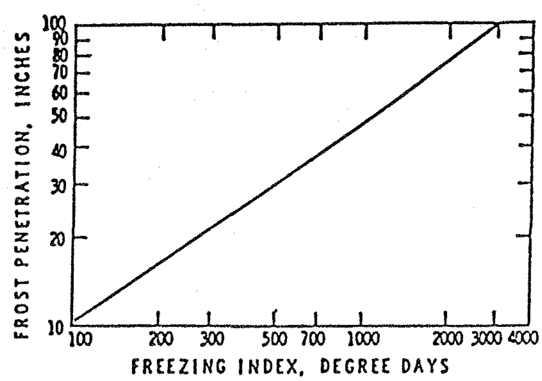


Figure 4 (a) Modified Design Curve (Brown, Canada)

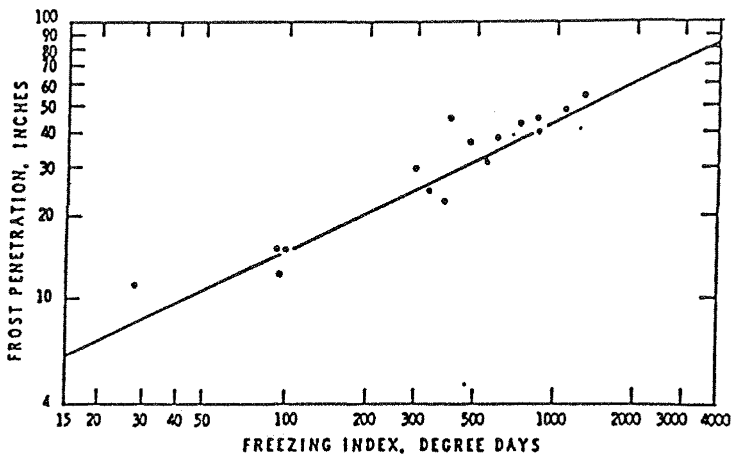


FIGURE 4 (b) Design curve," US Corps of Engineers. Maximum frost penetration under aircraft runways as dependent on air freezing index. (US Corps of Engineers, 1949)

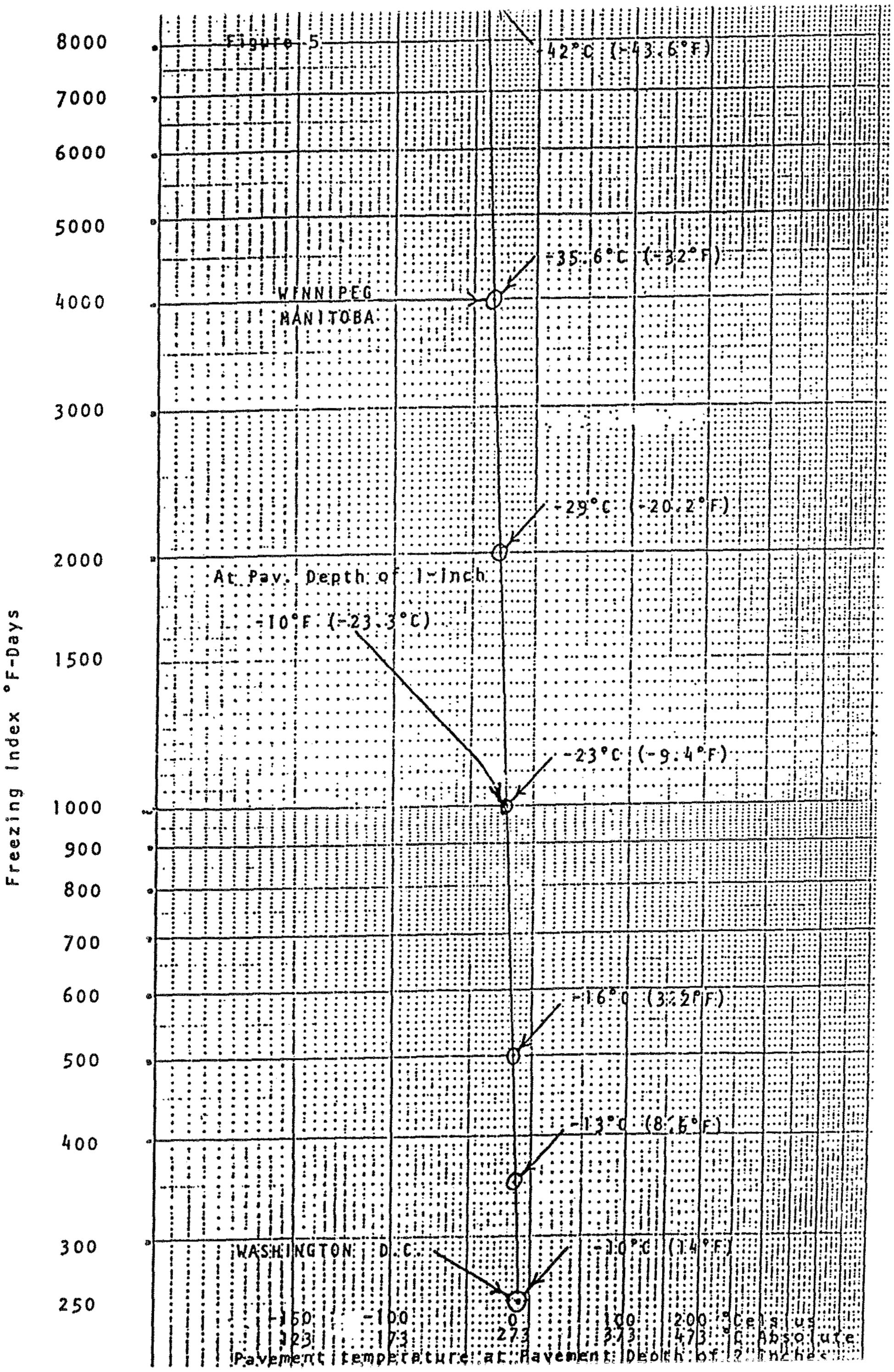


Figure 5
8000
7000
6000
5000
4000
3000
2000
1500
1000
900
800
700
600
500
400
300
250
Freezing Index °F-Days
-42°C (-43.6°F)
-35.6°C (-32°F)
WINNIPEG
MANITOBA
-29°C (-20.2°F)
At Pav. Depth of 1-inch
-10°F (-23.3°C)
-23°C (-9.4°F)
-16°C (3.2°F)
-13°C (8.6°F)
WASHINGTON D.C.
-10°C (14°F)
-150 -100 0 100 200 °Celsius
123 173 273 373 473 °C Absolute
Pavement temperature at Pavement Depth of 2 Inches

TABLE 1 INFLUENCE OF FREEZING INDEX ON MINIMUM PAVEMENT TEMPERATURE, °F, AT PAVEMENT DEPTH, INCHES

Freezing Index	MINIMUM PAVEMENT TEMPERATURE, °F, AT PAVEMENT DEPTH, INCHES										
	0.0	0.5	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0
9000	-44.6	-44.8	-44.6	-44.6	-44.6	-44.6	-40.7	-37.0	-31.9	-27.0	-24.3
8000	-42.9	-42.9	-42.9	-42.9	-42.8	-42.8	-38.9	-35.3	-30.4	-26.3	-22.9
7000	-41.0	-40.9	-40.9	-40.9	-40.8	-40.7	-37.0	-33.4	-28.6	-24.6	-21.3
6000	-38.8	-38.6	-38.5	-38.5	-38.5	-38.3	-34.7	-31.2	-26.5	-22.6	-19.4
5000	-36.2	-35.9	-35.7	-35.7	-35.7	-35.5	-32.0	-28.6	-24.0	-20.3	-17.1
4000	-33.0	-32.5	-32.3	-32.3	-32.2	-32.0	-28.6	-25.4	-21.0	-17.4	-14.4
3500	-31.1	-30.5	-30.3	-30.2	-30.1	-29.9	-26.6	-23.5	-19.2	-15.7	-12.7
3000	-28.8	-27.8	-27.8	-27.8	-27.7	-27.5	-24.2	-21.2	-17.1	-13.7	-10.0
2500	-26.2	-25.3	-25.0	-25.0	-24.8	-24.5	-21.5	-18.6	-14.5	-11.3	-8.6
2000	-22.9	-21.9	-21.6	-21.4	-21.2	-21.0	-10.0	-15.3	-11.4	-8.3	-5.8
1500	-18.6	-17.4	-17.0	-16.9	-16.6	-16.3	-13.6	-11.0	-7.4	-4.5	-2.1
1250	-15.9	-14.5	-14.1	-13.9	-13.6	-13.3	-10.7	-8.3	-4.8	-2.1	+0.2
1000	-12.5	-11.0	-10.6	-10.3	-10.0	-9.6	-7.2	-4.9	-1.7	+0.9	+3.1
750	-8.1	-6.4	-5.9	-5.6	-4.9	-4.8	-2.6	-0.5	+2.4	+4.8	+6.8
500	-1.9	+0.2	+0.7	+1.1	+1.6	+2.0	+3.9	+5.7	+8.3	+10.4	+12.0
250	+9.0	+11.6	+12.3	+12.8	+13.4	+13.9	+15.3	+16.6	+18.5	+20.0	+21.2
100	+23.8	+27.2	+28.0	+28.7	+29.5	+30.1	+30.8	+31.4	+32.3	+33.0	+33.6
Corresponding equations in terms of log temperature °R and log freezing index °F	Log T = 2.75208 – 0.03386 log FI	Log T = 2.75826 – 0.03542 log FI	Log T = 2.75979 – 0.03580 log FI	Log T = 2.76116 – 0.03618 log FI	Log T = 2.76261 – 0.03656 log FI	Log T = 2.76358 – 0.03677 log FI	Log T = 2.76056 – 0.03498 log FI	Log T = 2.75772 – 0.03329 log FI	Log T = 2.75417 – 0.03109 log FI	Log T = 2.75117 – 0.02923 log FI	Log T = 2.74857 – 0.02774 log FI

Freezing Index	MINIMUM PAVEMENT TEMPERATURE, °F, AT PAVEMENT DEPTH, INCHES													
	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
9000	-21.6	-19.2	-17.0	-15.2	-13.5	-11.7	-10.4	-9.2	-7.7	-6.5	-5.4	-4.3	-3.4	-2.6
8000	-20.2	-17.0	-15.7	-14.0	-12.3	-10.5	-9.3	-8.0	-6.6	-5.4	-4.4	-3.2	-2.3	-1.5
7000	-18.6	-16.3	-14.2	-12.6	-10.9	-9.1	-7.9	-6.7	-5.4	-4.1	-3.2	-2.0	-1.2	-0.4
6000	-16.0	-14.6	-12.5	-10.9	-9.3	-7.5	-6.4	-5.2	-3.9	-2.7	-1.7	-0.7	+0.2	+1.0
5000	-14.7	-12.5	-10.5	-8.9	-7.4	-5.7	-4.5	-3.4	-2.1	-1.0	-0.1	+1.0	+1.8	+2.5
4000	-12.0	-9.9	-8.0	-6.5	-5.0	-3.4	-2.3	-1.2	-0.0	+1.1	+2.0	+3.0	+3.8	+4.5
3500	-10.4	-8.4	-6.5	-5.0	-3.0	-2.0	-0.9	+0.1	+1.3	+2.4	+3.3	+4.2	+5.0	+5.7
3000	-8.5	-6.6	-4.8	-3.4	-1.9	-0.4	+0.6	+1.7	+2.8	+3.8	+4.7	+5.6	+6.4	+7.0
2500	-6.3	-4.4	-2.7	-1.4	-0.0	+1.5	+2.5	+3.5	+4.5	+5.6	+6.4	+7.3	+8.0	+8.6
2000	-3.6	-1.0	-0.2	+1.1	+2.4	+3.8	+4.8	+5.7	+6.7	+7.7	+8.5	+9.3	+10.0	+10.6
1500	+0.1	+1.6	+3.1	+4.3	+5.5	+6.8	+7.7	+8.6	+9.5	+10.4	+11.2	+12.0	+12.6	+13.2
1250	+2.1	+3.7	+5.2	+6.3	+7.5	+8.7	+9.6	+10.5	+11.3	+12.2	+12.9	+13.7	+14.3	+14.8
1000	+4.9	+6.4	+7.8	+8.8	+10.0	+11.1	+11.9	+12.7	+13.6	+14.4	+15.0	+15.7	+16.3	+16.8
750	+8.5	+9.9	+11.1	+12.1	+13.1	+14.1	+14.9	+15.7	+16.4	+17.2	+17.8	+18.4	+19.0	+19.4
500	+13.6	+14.8	+15.9	+16.7	+17.6	+18.5	+19.2	+19.9	+20.5	+21.1	+21.7	+22.2	+22.7	+23.1
250	+22.4	+23.3	+24.1	+24.7	+25.4	+26.0	+26.6	+27.1	+27.5	+28.0	+28.4	+28.8	+29.2	+29.5
100	+34.3	+34.8	+35.2	+35.5	+35.9	+36.1	+36.5	+36.8	+36.9	+37.2	+37.5	+37.6	+37.9	+38.1
Corresponding equations in terms of log temperature °R and log freezing index °F	Log T = 2.74716 – 0.02670 log FI	Log T = 2.74554 – 0.02568 log FI	Log T = 2.74404 – 0.02476 log FI	Log T = 2.74279 – 0.02401 log FI	Log T = 2.74180 – 0.02334 log FI	Log T = 2.74037 – 0.02252 log FI	Log T = 2.73989 – 0.02210 log FI	Log T = 2.73915 – 0.02160 log FI	Log T = 2.73796 – 0.02096 log FI	Log T = 2.73722 – 0.02046 log FI	Log T = 2.73660 – 0.02006 log FI	Log T = 2.73579 – 0.01957 log FI	Log T = 2.73536 – 0.01924 log FI	Log T = 2.73485 – 0.01892 log FI

TABLE 2 INFLUENCE OF FREEZING INDEX ON MAXIMUM PAVEMENT TEMPERATURE, °F, AT PAVEMENT DEPTH, INCHES

Freezing Index	MAXIMUM PAVEMENT TEMPERATURE, °F AT PAVEMENT DEPTH, INCHES													
	0.0	0.5	0.75	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0	8.0	9.0
9000	106.4	103.7	103.0	102.6	102.0	101.5	97.3	93.9	88.4	84.1	80.7	77.8	75.2	72.7
8000	107.3	104.6	103.9	103.4	102.8	102.3	98.2	94.7	89.3	84.9	81.5	78.7	76.0	73.6
7000	108.3	105.6	104.9	104.4	103.8	103.2	99.1	95.7	90.3	85.9	82.5	79.7	77.0	74.6
6000	109.6	106.8	106.0	105.5	104.9	104.3	100.2	96.8	91.4	87.0	83.6	80.8	78.2	75.7
5000	111.0	108.1	107.4	106.9	106.2	105.6	101.5	98.1	92.7	88.4	85.0	82.1	79.5	77.1
4000	112.8	109.8	109.0	108.5	107.8	107.2	103.1	99.7	94.3	90.0	86.6	83.8	81.2	78.8
3500	113.9	110.8	110.0	109.5	108.8	108.2	104.1	100.7	95.3	91.0	87.6	84.8	82.2	79.8
3000	115.1	112.0	111.1	110.6	109.9	109.3	105.2	101.8	96.4	92.1	88.7	85.9	83.4	81.0
2500	116.6	113.3	112.5	112.0	111.2	110.6	106.5	103.1	97.7	93.5	90.1	87.3	84.7	82.4
2000	118.4	115.0	114.2	113.6	112.8	112.2	108.1	104.7	99.4	95.1	91.7	89.0	86.8	84.1
1500	120.7	117.2	116.3	115.7	114.9	114.2	110.2	106.8	101.5	97.2	93.8	91.1	88.6	86.3
1250	122.2	118.6	117.7	117.1	116.2	115.5	111.5	108.1	102.8	98.6	95.2	92.5	90.0	87.7
1000	124.0	120.3	119.4	118.8	117.9	117.2	113.1	109.8	104.5	100.3	96.9	94.2	91.6	89.4
750	126.3	122.5	121.5	120.9	120.0	119.3	115.2	111.9	106.6	102.4	99.0	96.4	93.8	91.7
500	129.7	125.6	124.6	124.0	123.0	122.2	118.2	114.9	109.6	105.5	102.1	99.5	96.9	94.8
250	135.4	131.0	129.9	129.2	128.1	127.3	123.3	120.0	114.8	110.7	107.3	104.8	102.3	100.3
100	143.1	138.2	137.0	136.2	135.0	134.1	130.1	126.9	121.7	117.7	114.3	111.9	109.5	107.6
Corresponding equations in terms of log temperature °R and log freezing index °F	Log T = 2.80808 − 0.01396 log FI	Log T = 2.80298 − 0.01318 log FI	Log T = 2.80177 − 0.01302 log FI	Log T = 2.80099 − 0.01291 log FI	Log T = 2.79963 − 0.01268 log FI	Log T = 2.79877 − 0.01257 log FI	Log T = 2.79617 − 0.01272 log FI	Log T = 2.79403 − 0.01286 log FI	Log T = 2.79072 − 0.01311 log FI	Log T = 2.78815 − 0.01333 log FI	Log T = 2.78575 − 0.01341 log FI	Log T = 2.78445 − 0.01367 log FI	Log T = 2.78283 − 0.01380 log FI	Log T = 2.78205 − 0.01412 log FI

Freezing Index	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
9000	70.6	68.9	67.2	65.6	64.1	62.8	61.4	60.3	59.2	58.2	57.3
8000	71.5	69.8	68.1	66.5	65.0	63.7	62.3	61.2	60.1	59.1	58.2
7000	72.5	70.8	69.1	67.5	66.0	64.7	63.3	62.2	61.1	60.1	59.2
6000	73.6	71.9	70.2	68.7	67.2	65.9	64.5	63.4	62.3	61.3	60.4
5000	75.0	73.3	71.6	70.1	68.6	67.3	66.0	64.9	63.7	62.7	61.9
4000	76.7	75.0	73.3	71.8	70.3	69.0	67.7	66.6	65.5	64.5	63.6
3500	77.7	76.0	74.3	72.8	71.3	70.0	68.7	67.6	66.6	65.6	64.6
3000	78.9	77.2	75.5	74.0	72.5	71.0	70.5	68.9	68.3	66.8	65.9
2500	80.3	78.6	76.9	75.4	73.9	72.6	71.4	70.3	69.2	68.2	67.3
2000	82.0	80.3	78.6	77.1	75.7	74.4	73.2	72.1	71.0	70.0	69.0
1500	84.2	82.5	80.8	79.3	77.9	76.6	75.4	74.3	73.3	72.3	71.3
1250	85.6	83.9	82.2	80.8	79.3	78.1	76.9	75.8	74.7	73.7	72.8
1000	87.3	85.6	83.9	82.5	81.1	79.8	78.7	77.6	76.5	75.5	74.5
750	89.6	87.9	86.2	84.7	83.4	82.1	81.0	79.9	78.9	77.9	76.8
500	92.7	91.0	89.3	87.9	86.6	85.3	84.3	83.2	82.1	81.1	80.1
250	98.2	96.5	94.8	93.4	92.1	90.9	89.9	88.8	87.8	86.8	85.7
100	105.5	103.8	102.1	100.7	99.5	98.3	97.4	96.3	95.4	94.4	93.2
Corresponding equations in terms of log temperature °R and log freezing index °F	Log T = 2.78055 − 0.01417 log FI	Log T = 2.77933 − 0.01422 log FI	Log T = 2.77810 − 0.01426 log FI	Log T = 2.77726 − 0.01437 log FI	Log T = 2.77664 − 0.01454 log FI	Log T = 2.77594 − 0.01464 log FI	Log T = 2.77571 − 0.01487 log FI	Log T = 2.77491 − 0.01490 log FI	Log T = 2.77435 − 0.01500 log FI	Log T = 2.77362 − 0.01503 log FI	Log T = 2.77251 − 0.01492 log FI

Table 3

Effect of Freezing Index on Minimum Pavement Temperature, °F, at Pavement Depth in Inches
(Semi-log Relationship Between Minimum Pavement Temperature and Pavement Depth in Inches)

Freezing Index	Minimum Pavement Temperature, °F, at Pavement Depth, inches								
	0.0	0.5	1.0	2.0	4.0	8.0	12.0	16.0	20.0
9000	-93.7	-93.7	-93.7	-93.7	-73.5	-54.2	-42.6	-34.6	-28.8
7000	-68.7	-68.7	-68.7	-68.7	-52.5	-36.4	-26.9	-20.2	-15.5
5000	-44.4	-44.4	-44.4	-44.2	-31.5	-18.8	-11.2	-6.1	-2.2
4000	-33.0	-32.5	-32.3	-32.0	-21.0	-9.9	-3.4	+1.1	+4.5
3000	-21.8	-20.7	-20.3	-19.8	-10.5	-1.0	+4.4	+8.3	+11.2
2000	-10.6	-9.0	-8.2	-7.5	0.0	+7.8	+12.3	+15.4	+17.9
1000	+0.6	+2.8	+3.8	+4.7	+10.5	+16.7	+20.1	+22.6	+24.5
500	+6.2	+8.7	+9.8	+10.6	+15.8	+21.1	+24.0	+26.2	+27.8
250	+9.0	+11.6	+12.8	+13.9	+18.4	+23.3	+26.0	+28.0	+29.5

Table 4

Effect of Freezing Index on Maximum Pavement Temperature, °F, at Pavement Depth in Inches
(Semi-log Relationship Between Maximum Pavement Temperature and Pavement Depth in Inches)

Freezing Index	Maximum Pavement Temperature, °F, at Pavement Depth, inches								
	0.0	0.5	1.0	2.0	4.0	8.0	12.0	16.0	20.0
9000	82.7	81.5	81.1	80.4	67.0	53.1	44.6	38.1	34.1
7000	94.7	92.8	91.9	91.1	77.9	64.3	56.1	49.9	45.9
5000	106.8	104.1	103.0	101.9	88.8	75.4	67.6	61.8	59.0
4000	112.8	109.8	108.5	107.2	94.3	81.2	73.3	67.7	63.6
3000	118.9	115.5	114.0	112.6	99.8	86.8	79.0	73.6	70.2
2000	124.9	121.1	119.5	117.9	105.2	92.9	84.8	79.5	75.4
1000	130.9	126.8	125.1	123.3	110.7	98.1	90.5	85.5	81.5
500	133.9	129.6	127.8	126.0	113.4	100.9	93.4	88.4	84.3
250	135.4	131.0	129.2	127.3	114.8	102.3	94.8	89.9	85.7

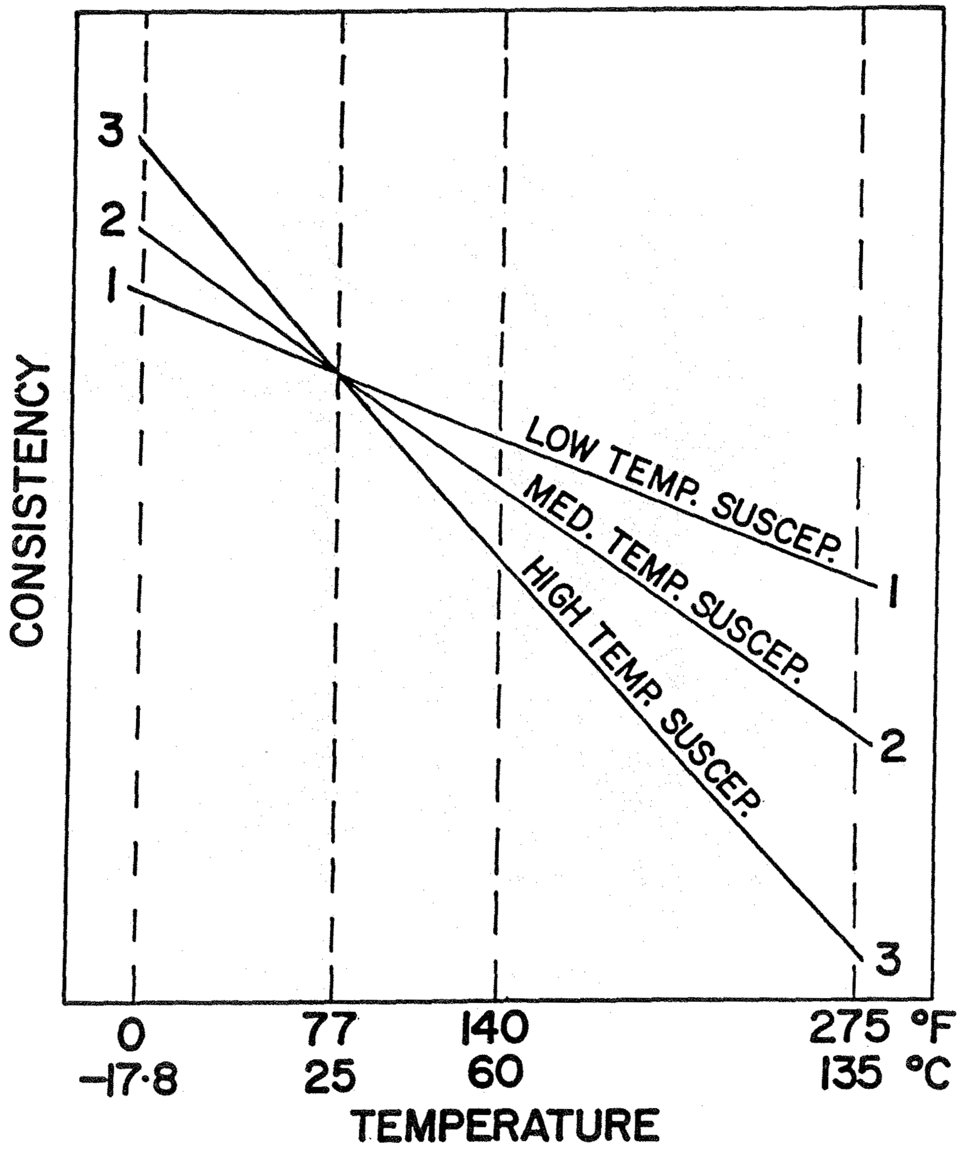


Fig. 6 SKETCH ILLUSTRATING DIFFERENT TEMPERATURE SUSCEPTIBILITIES OF PAVING ASPHALTS

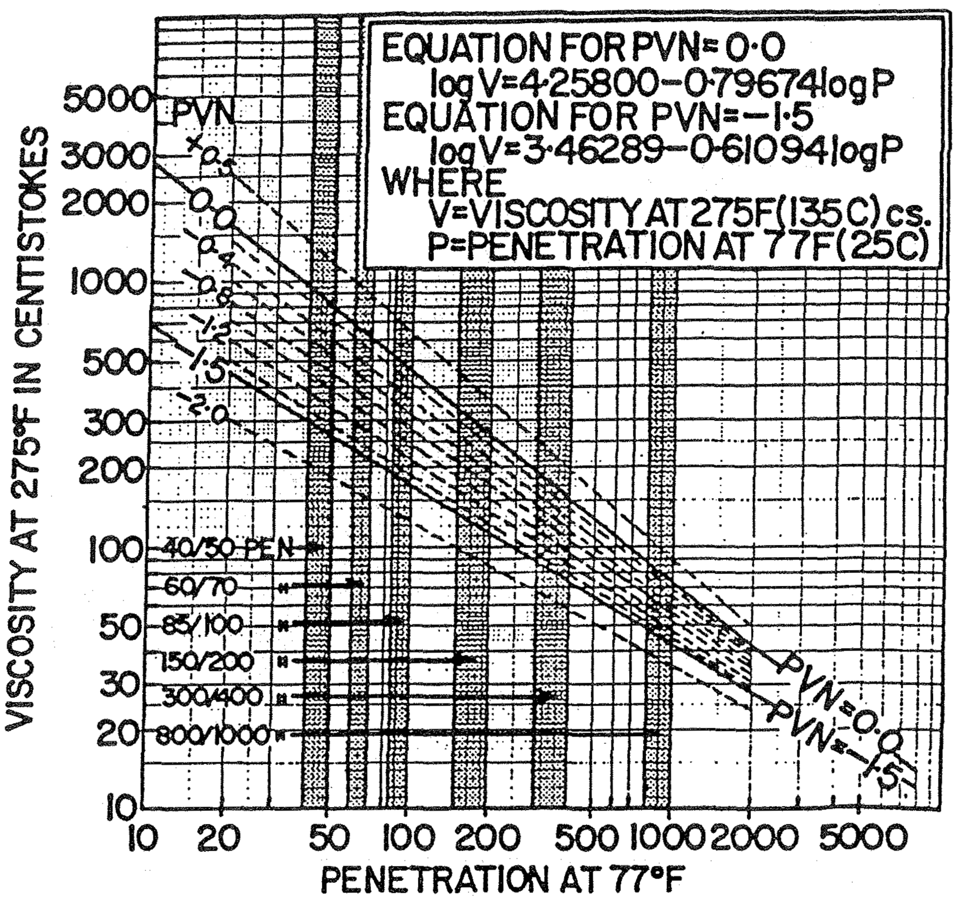


FIGURE 7 A CHART FOR THE DETERMINATION OF APPROXIMATE VALUES FOR PEN-VIS NUMBERS FOR ASPHALT CEMENTS.

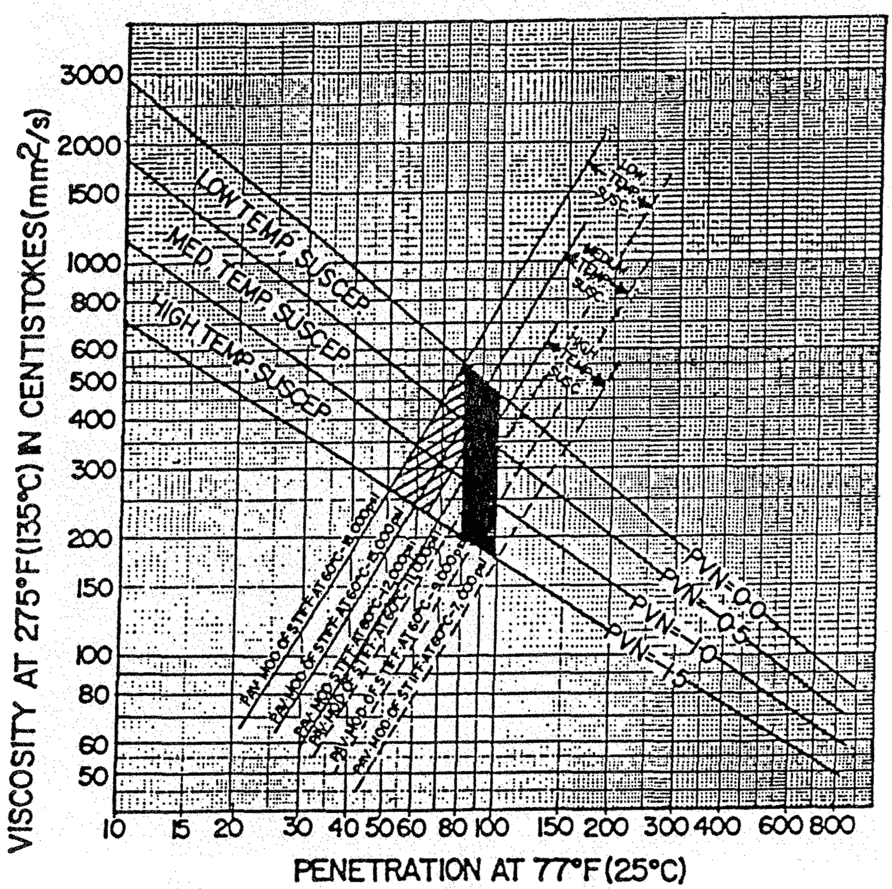


Fig. 8 ILLUSTRATING HOW PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY CAN BE MADE TO WORK FOR OR AGAINST ENGINEERS IN WARM CLIMATES.

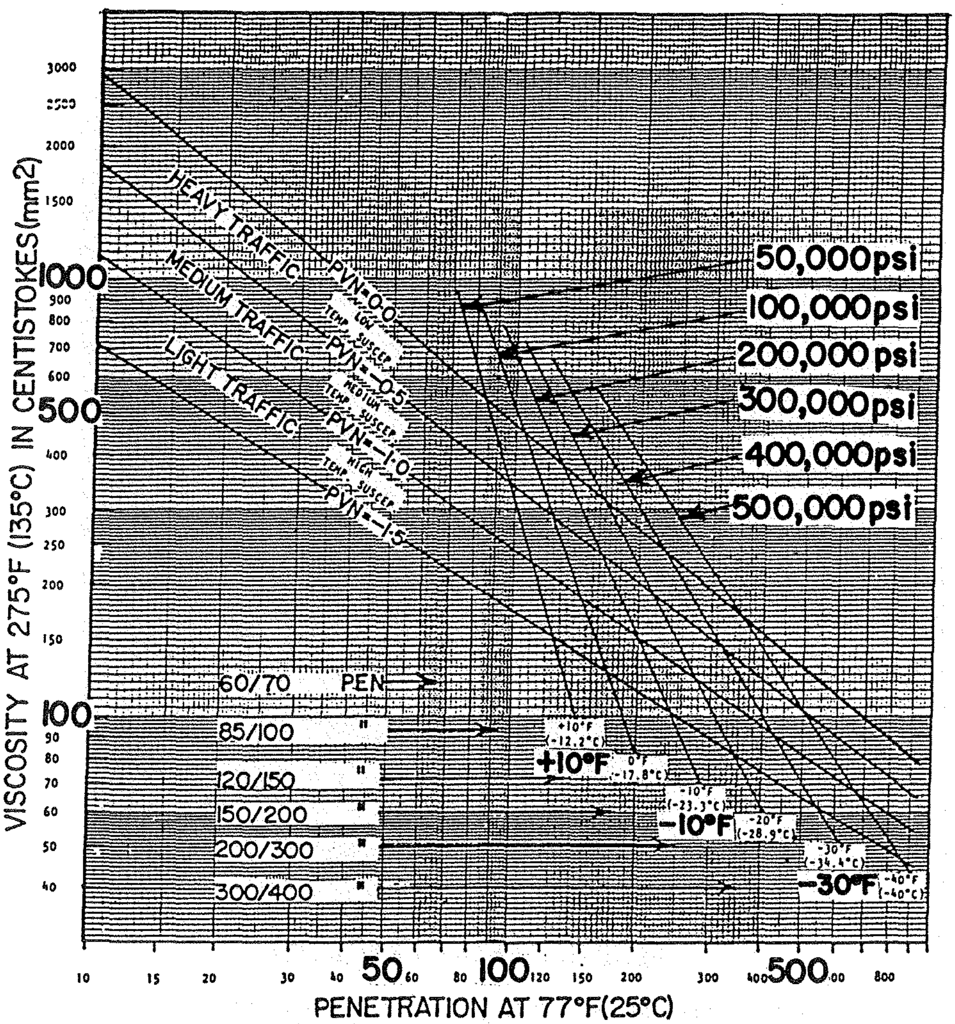


Fig. 9 CHART FOR SELECTING PAVING ASPHALTS WITH VARIOUS COMBINATIONS OF TEMPERATURE SUSCEPTIBILITIES AND PENETRATIONS AT 25°C TO AVOID LOW TEMPERATURE TRANSVERSE PAVEMENT CRACKING AT SELECTED MINIMUM WINTER PAVEMENT TEMPERATURES.

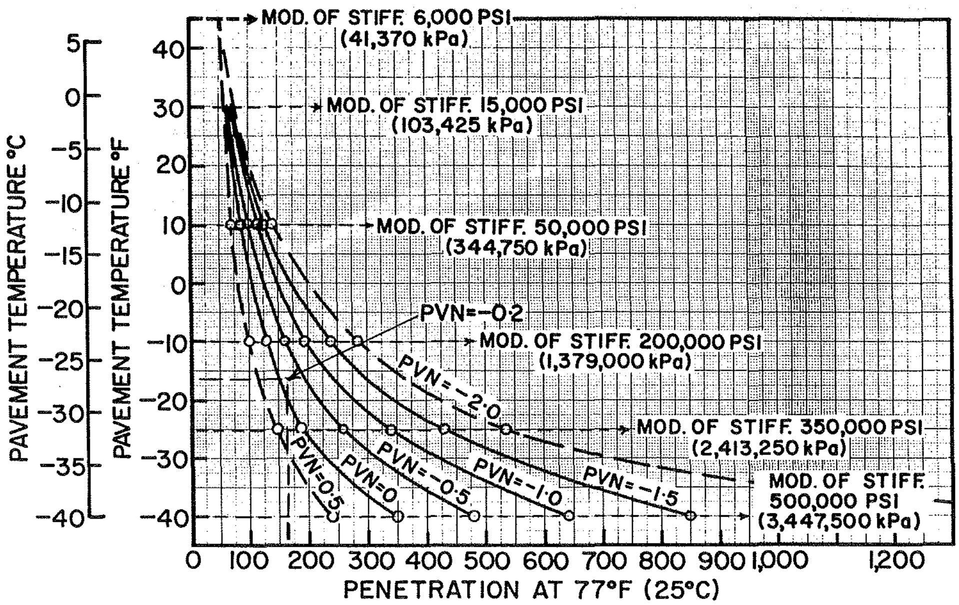


FIGURE 10 CONTINUOUS SCALE FOR LOW PAVEMENT TEMPERATURES VERSUS CORRESPONDING MINIMUM PAVING ASPHALT PENETRATIONS AT 77F (25C) TO AVOID LOW TEMPERATURE TRANSVERSE PAVEMENT CRACKING

TABLE 5

Minimum Modulus of Stiffness and Corresponding Minimum Ontario Marshall Stability Requirements For Heavy, Medium and Light Traffic.

Ontario Minimum Marshall Stability at 60°C (140°F)	Corresponding Minimum Modulus of Stiffness at Maximum Pavement Temperature
Heavy Traffic 8900 N (2000 lb)	20,000 psi (138 MPa)
Medium Traffic 6700 N (1500 lb)	15,000 psi (103 MPa)
Light Traffic 4400 N (1000 lb)	10,000 psi (69 MPa)

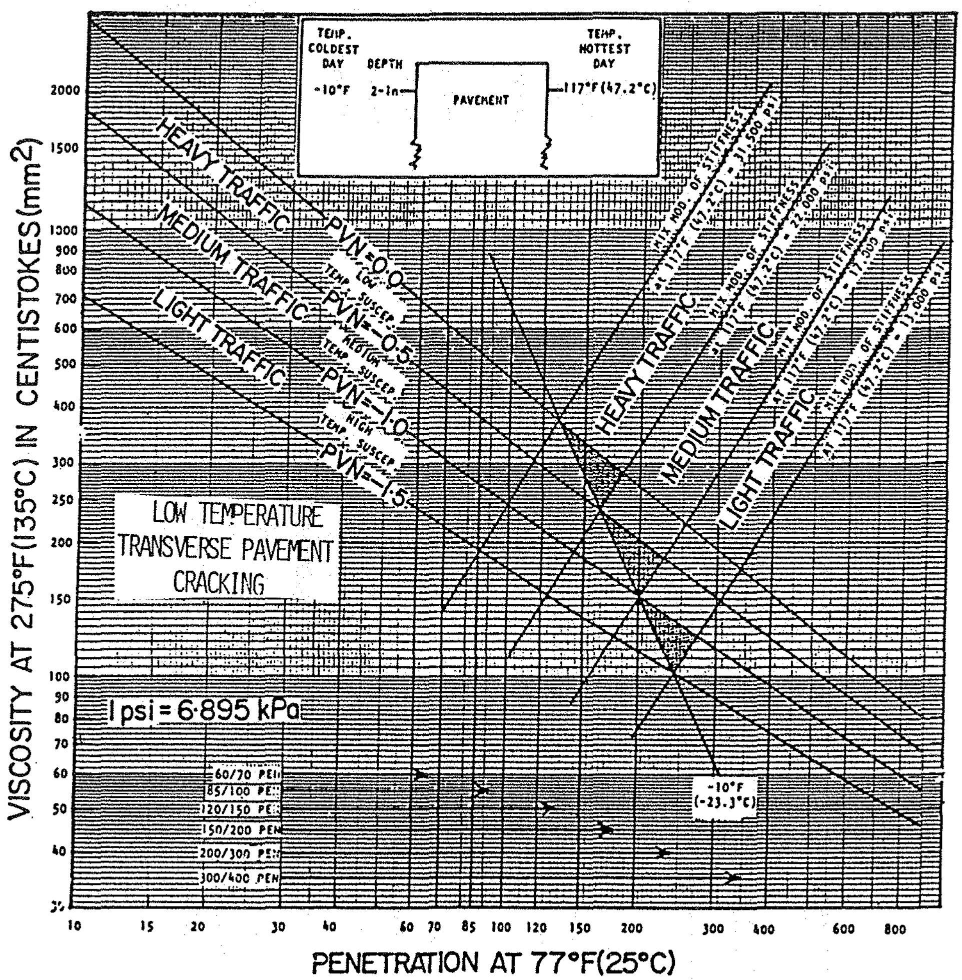


Figure 11 Illustrating Selection of Combinations of Temperature Susceptibility (PVN) and Penetration at 25°F for Paving Asphalts For Heavy, Medium and Light Traffic in Cold Climates.

TABLE 6

Influence of Maximum Summer Pavement Temperatures, Paving Asphalt Temperature Susceptibilities and Corresponding Penetrations at 25°C, On Pavement Moduli Stiffness For 2-Inch Surface, Binder and Base Course Layers.

Service Temp. (Max. Summer Pav. Temp.)	Time of Loading Seconds	Temperature Susceptibility	PVN	Pen. At 25°C	Base Temp. °C	Service Temp. Minus Base Temp. °C	Mod. of Stiff. Pav. Asphalt psi	Mod. of Stiff. Corresp. Pav. psi	Average Pav. Mod. of Stiff psi
2-Inch Surface Course, Pavement Depth = one Inch									
113°F (45°C)	0.012	Low	0.0	165	42	+ 3.0	18.5	28,000	24,500
113°F (45°C)	0.012	Medium	-0.5	215	38.2	+ 6.8	11.6	21,000	18,000
113°F (45°C)	0.012	High	-1.0	275	34.8	+10.2	6.9	15,000	12,750
113°F (45°C)	0.012		-1.5	345	32.2	+12.8	5.0	10,500	
2-Inch Binder Course, Pavement Depth = 3 Inches									
105°F (40.6°C)	0.016	Low	0.0	143	43.6	- 3.0	33.7	40,000	35,000
105°F (40.6°C)	0.016	Medium	-0.5	182	39.9	+ 0.7	21.0	30,000	26,000
105°F (40.6°C	0.016	High	-1.0	225	36.9	+ 3.7	12.8	22,000	19,000
105°F (40.6°C)	0.016		-1.5	275	34.1	+ 6.5	8.6	16,000	
2-Inch Base Course, Pavement Depth = 5 Inches									
95°F (35°C)	0.02	Low	0.0	123	45.4	-10.2	84.0	80,000	69,500
95°F (35°C)	0.02	Medium	-0.5	150	41.8	- 6.8	55.0	59,000	50,500
95°F (35°C)	0.02	High	-1.0	180	38.9	- 3.9	36.8	42,000	36,000
95°F (35°C)	0.02		-1.5	217	36.1	- 1.1	27.6	30,000	

1	2	3	4	5	6	7
PAVEMENT LAYER	AVERAGE LAYER TEMPERATURE	AVERAGE PAVEMENT MODULUS OF STIFFNESS PSI				
		HEAVY TRAFFIC PAVEMENTS				
2-in Surface	113°F (45°C)	A* 24,500	A 24,500	A 24,500	A 24,500	
2-in Binder	105°F (40.6°C)	A 35,000	B* 26,000	B 26,000	C 19,000	
2-in Base	95°F (23°C)	A 69,500	B 50,500	C* 36,000	C 36,000	
		MEDIUM TRAFFIC PAVEMENTS				
2-in Surface	113°F (45°C)	B 18,000	B 18,000	B 18,000		
2-in Binder	105°F (40.6°C)	B 26,000	B 26,000	C 19,000	----	
2-in Base	95°F (35°C)	B 50,5000	C 36,000	C 36,000		
		LIGHT TRAFFIC PAVEMENTS				
2-in Surface	113°F (45°C)	C 12,750				
2-in Binder	105°F (40.6°C)	C 19,000	----	----	----	
2-in Base	95°F (35°C)	C 36,000				

TEMP. COLDEST DAY	DEPTH		TEMP. HOTTEST DAY
-20°F	1-in	SURFACE 2-in	113°F (45°C)
-14°F	3-in	BINDER 2-in	105°F (40.6°(
- 7°F	5-in	BASE 2-in	95°F (35°C)

*A - 2-in pavement layer contains paving asphalt of low temperature susceptibility, PVN = 0.0 to -0.5.

*B - 2-in pavement layer contains paving asphalt of medium temperature susceptibility, PVN = -0.5 to -1.0.

*C - 2-in pavement layer contains paving asphalt of high temperature susceptibility, PVN = -1.0 to -1.5.

FIGURE 12

SELECTING PAVING ASPHALTS OF DIFFERENT TEMPERATURE SUSCEPTIBILITIES FOR SURFACE BINDER AND BASE COURSE LAYERS

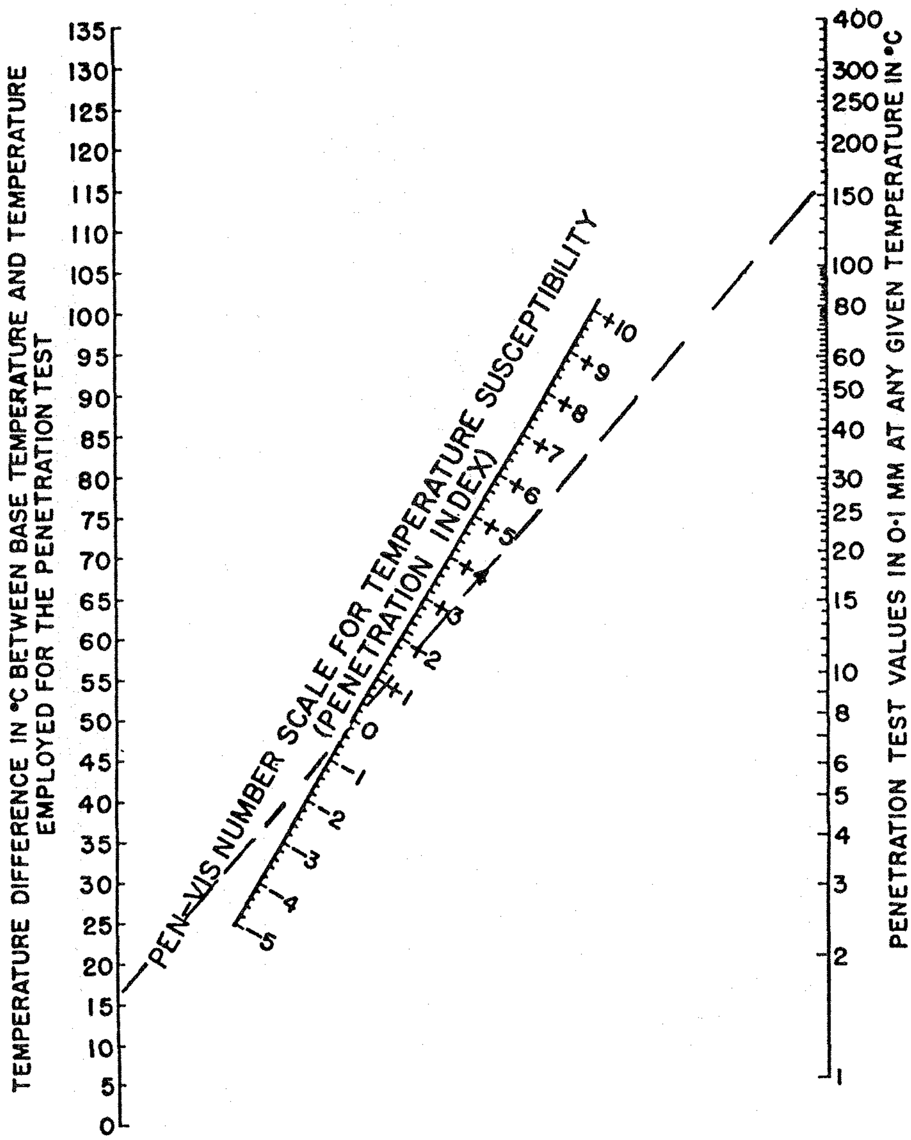


FIGURE 13 SUGGESTED MODIFICATION OF HEUKELOM'S VERSION OF PFEIFFER'S AND VAN DOORMAAL'S NOMOGRAPH TO DEMONSTRATE RELATIONSHIP BETWEEN VALUES FOR PENETRATION, PEN-VIS NUMBER, AND BASE TEMPERATURE FOR ASPHALT CEMENTS.

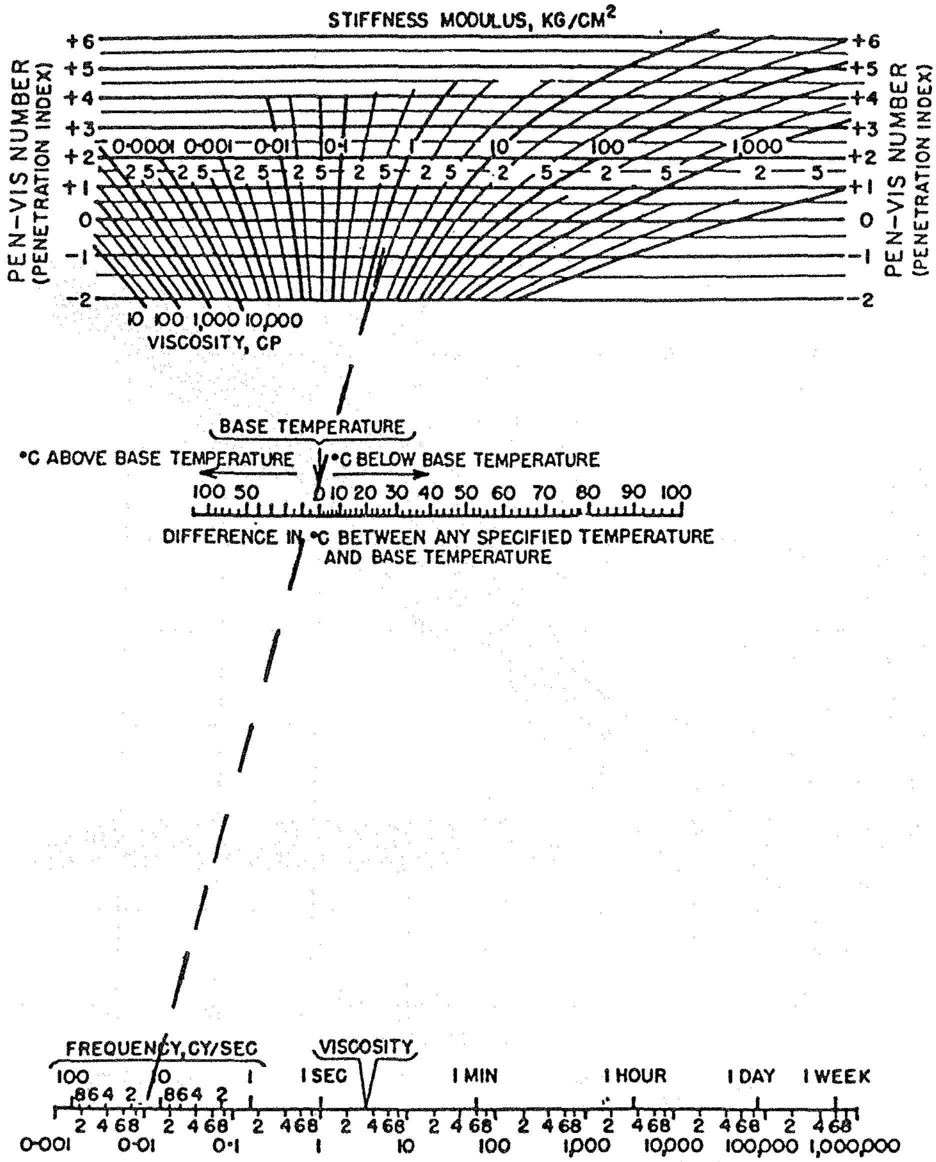


FIG. 14 SUGGESTED MODIFICATION OF HEUKELOM'S AND KLOMP'S VERSION OF VAN DER POEL'S NOMOGRAPH FOR DETERMINING MODULUS OF STIFFNESS OF ASPHALT CEMENTS.

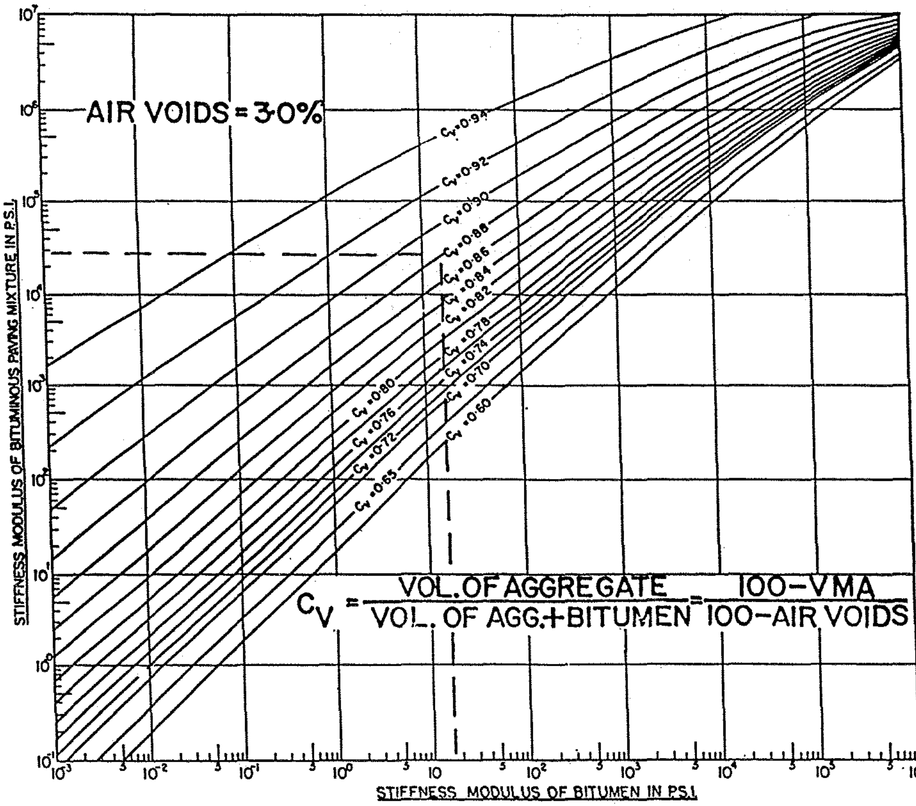


FIGURE 15 NOMOGRAPH FOR DETERMINING MODULI OF STIFFNESS OF ASPHALT PAVING MIXTURES (WITH CREDIT TO VAN DER POEL)

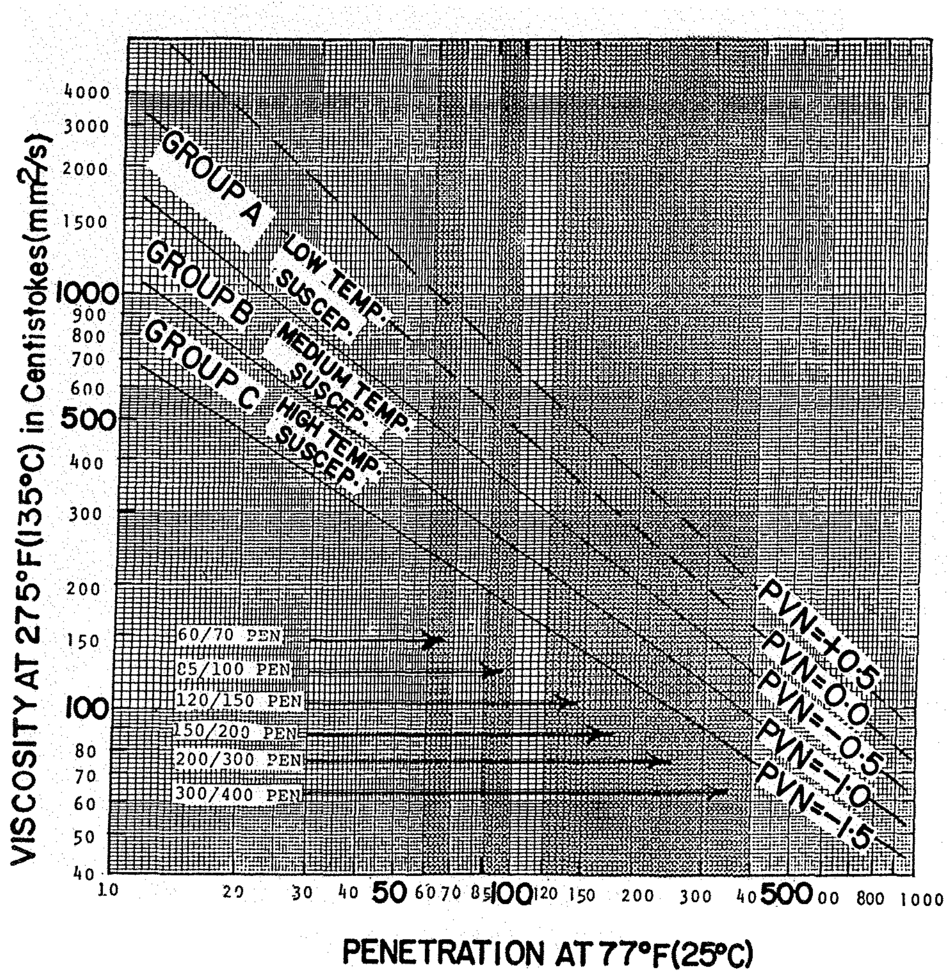


Figure 16 ILLUSTRATING RELATIONSHIPS BETWEEN PENETRATIONS AT 25°C, VISCOSITIES AT 135°C AND TEMPERATURE SUSCEPTIBILITIES OF PAVING ASPHALTS

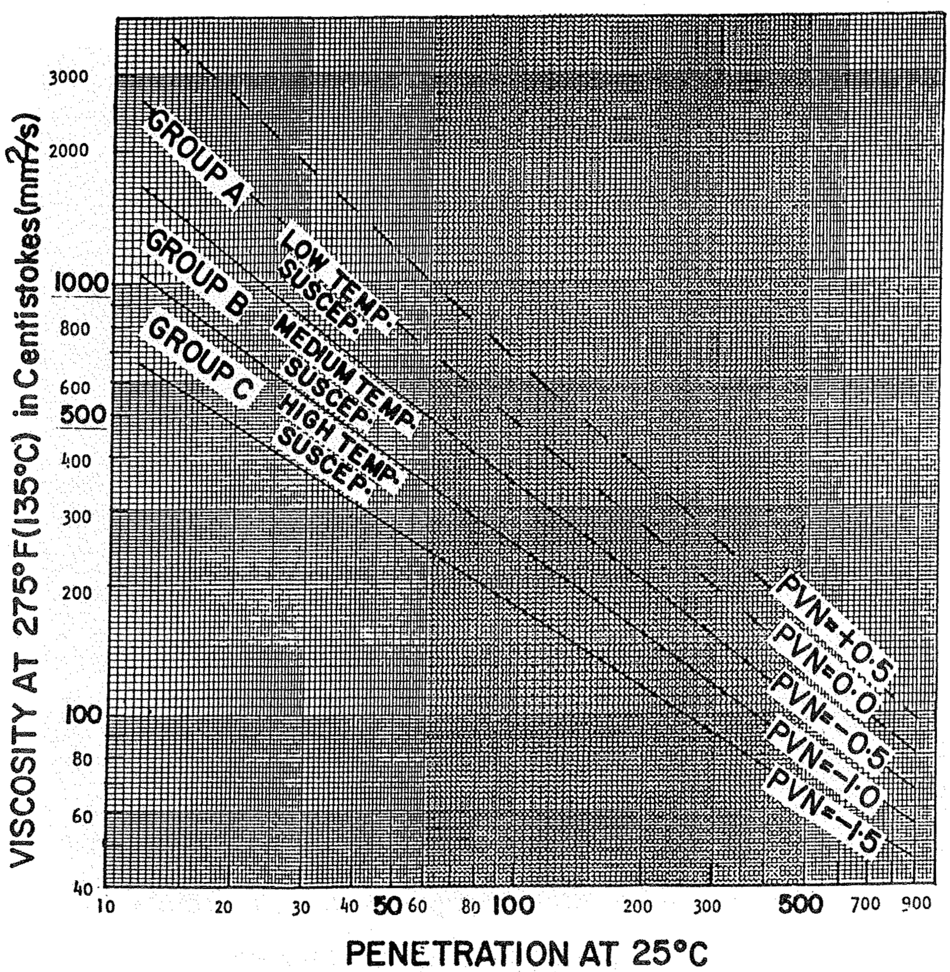


Figure 17 PROBABLE FUTURE SPECIFICATION FOR PAVING ASPHALTS BASED ON PENETRATION AT 25°C and TEMPERATURE SUSCEPTIBILITY

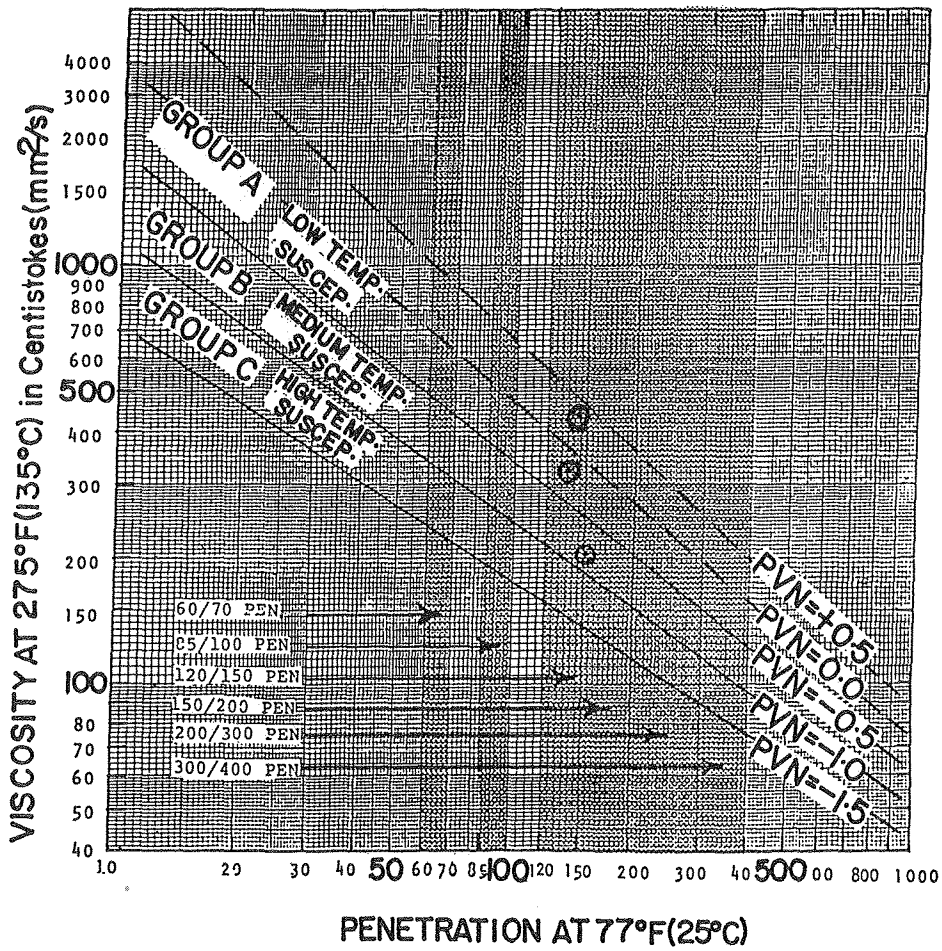


Figure 18 INFLUENCE OF A POLYMER ON THE TEMPERATURE SUSCEPTIBILITY OF A PAVING ASPHALT.