Reduction in Transverse Pavement Cracking by Use of Softer Asphalt Cements

By Dr. Norman W. McLeod*

SYNOPSIS

This paper indicates that transverse pavement cracking in Canada is caused primarily by low winter temperatures, and that it can be dramatically reduced and even eliminated by the use of softer grades of asphalt cement.

Evidence for this is provided by observation and photographs of pavements in Canada, and by the analysis of pavement samples. These show that transverse cracking is severe when 150/200 or 85/100 penetration asphalts are used in colder regions, but that it is reduced or disappears when the asphalt binder is 300/400 penetration or SC 3000 (SC 5).

Theoretical considerations based on the work of Rader, Van der Poel, Heukelom and Klomp, and Hills and Brien, are presented, which support the conclusion that the use of softer grades of asphalt cement will minimize transverse pavement cracking.

Because soft asphalt cements are approximately the same price as harder asphalt cements, there should normally be little or no increase in the initial pavement cost by changing to soft asphalt cements to reduce transverse pavement cracking. However, this change would result in a substantial annual savings in the maintenance cost of filling from 100 to 300 or more cracks per mile per year.

Since asphalt cements must also provide pavements with sufficient stability for hot weather traffic, engineering experience and sound judgment are required when deciding how soft an asphalt cement can be selected to reduce transverse cracking in cold weather.

Based on consideration of low temperature transverse pavement cracking, evidence is presented that firmly opposes grading of asphalt cements by viscosity at 140°F, and supports their continued grading by penetration at 77°F.

Key Words: Transverse pavement cracking, asphalt cements, modulus of stiffness, penetration index, temperature susceptibility, low temperature, penetration, viscosity, freezing index.

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INTRODUCTION

This paper reviews the results of four years of research on the most serious current asphalt pavement performance problem in Canada, which is transverse cracking (1, 2, 3, 4). Initially this problem was thoroughly investigated in the field. As we interpret the evidence, the road itself is trying to tell us that transverse pavement cracking in Canada is associated with cold weather, and that the simplest solution to this problem is the use of softer grades of asphalt cements. Following this field study, an attempt has been made to obtain theoretical support for the conclusion that the use of softer grades of asphalt cement will greatly reduce or eliminate transverse cracking. Therefore the subject matter of this paper will be presented in two principal parts:

(a) evidence from the field that transverse pavement cracking can be drastically reduced and even eliminated by using softer grades of asphalt cements

(b) theoretical evidence supporting this conclusion.

In addition, it will be shown that insofar as transverse pavement cracking is concerned, the conclusions presented in this paper oppose the grading of asphalt cements by viscosity at 140°F, and support their continued grading by penetration at 77°F.

Most of the subject matter of this paper was initially presented at the 1968 annual meeting of the Highway Research Board (5), at Washington, D.C., in January, and at the summer Highway Research Board meeting at Denver in August (6). However, additional information on pavement samples, has been obtained since that time, and has been included in the present paper.

1. Location of the Transverse Pavement Cracking Problem in Canada

The hatched portion of Figure 1 indicates that transverse pavement cracking is a very serious problem in Canada in the region extending from the Rocky Mountains to the mouth of the St. Lawrence River. In this region, it is not unusual for asphalt pavements on granular bases to be cracked transversely at intervals ranging from about five to about thirty feet. Transverse cracking of asphalt pavements is much less severe in Newfoundland, in the portion of the Maritime Provinces adjacent to the Atlantic Coast, in Southern British Columbia, and in Southern Ontario, where relatively mild winter weather prevails. Figure 1 also gives the location of the Trans-Canada Highway.

Figure 2 indicates that the freezing index ranges from 1,000 to 4,000 in the area of severe transverse pavement cracking shown in Figure 1. Figure 2 also indicates the location of each pavement illustrated in Figures 5 to 25.

Figure 3 demonstrates that freezing indices ranging from 1,000 to more than 3,000 also occur in Montana, Wyoming, North Dakota, South Dakota, Minnesota, Iowa, Wisconsin, Michigan, Vermont, New Hampshire and Maine. Technical publications indicate that the transverse cracking of asphalt pavements is a serious problem in the Northern United States (7, 8, 9, 10, 11).

2. General Evidence Relating Transverse Pavement Cracking to Hardness of Asphalt Cement.

In Canada at least, the transverse cracking of asphalt pavements on rural highways did not become a serious problem until harder grades of asphalt cement were introduced into hot mixes in the 1950's. In the first paving programs for rural highways in the 1930's, road mixes containing liquid asphalt binders such as SC 2, MC 2, or equivalent were commonly used. Transverse pavement cracking was not a problem. In the later 1930's, plant-mix pavements containing SC 4, SC 5, MC 4, and MC 5 were gradually introduced. Just before and immediately after World War II, the use of SC 6 became quite common.There was still little or no transverse pavement cracking. Following passage of the Trans-Canada Highway Act in 1949, it was felt that the higher construction standards adopted justified the use of harder grades of asphalt cement. Throughout Canada, 150/200 penetration asphalt became generally employed, with considerable use of the 85/100 penetration in Ontario and Quebec. Since the introduction of these harder grades of asphalt cement, the transverse cracking of asphalt pavements has eventually become a matter of grave concern. Consequently, the history of asphalt pavement construction in Canada indicates that the serious transverse cracking of pavements is associated with the use of harder grades of asphalt cements. It also implies that this transverse cracking problem could be largely avoided, and probably completely eliminated in some areas, by returning to the use of softer grades of asphalt cement.

In May and June of 1966, the author was driven over about 600 miles of roads in Southern Norway. The most impressive feature of these roads is the relative absence of transverse pavement cracking. On enquiry, it was learned that most of the pavements on these roads contained 300 penetration asphalt. To ensure 300 penetration, the specification stipulates a penetration range at 77°F of 280 to 320. Occasionally 200/500 penetration is used.

It is common experience in Canada, for pavements that appear almost perfect when a few months old, to become badly blemished with numerous transverse cracks several years later. Asphalt cements in pavements harden with time in service due to poor design or construction practice. Figure 4 illustrates the influence of the air voids in a series of pavements when rolling was complete, on the rate of hardening of the asphalt cement (12). The higher the air voids due to poor compaction, the faster is the rate of hardening of the asphalt cement. A low asphalt content due to poor design also leads to rapid hardening of the asphalt cement. At some critical asphalt hardness, the pavement loses its flexibility or its ability to stretch as required under low temperature contraction stresses, and transverse pavement cracking begins to occur.

For more than 30 years, the Alberta Department of Highways has used a mixed prime instead of spraying asphalt primer onto the surface of the compacted granular base before surfacing with hot-mix. For this mixed prime, MC 2 or MC 3 is road-mixed or plant-mixed into the top two or three inches of granular base. This mixed prime layer may carry traffic for from two to four years before a hot-mix pavement, usually 4 inches thick, is laid over it. It has been Alberta experience that only minor transverse cracking ever develops in the mixed prime layer with its liquid asphalt binder. On the other hand, usually within two to three years after the hot-mix pavement containing 150/200 or 200/300 penetration asphalt cement has been placed, serious transverse pavement cracking begins to develop.

Each of the above four illustrations indicates that transverse pavement cracking is associated with the hardness of the asphalt cement.

3. Photographic Evidence That Transverse Pavement Cracking Is Related to the Hardness of the Asphalt Cement.

Figures 5 to 25 illustrate typical performance of dense graded hot-mix pavements in Ontario, Alberta, Saskatchewan, and Manitoba. They provide photographic evidence of the association of cold weather transverse pavement cracking with the hardness of the asphalt cement. The principal difference between these pavements concerns the grades of asphalt employed, which includes 85/100 and 150/200 penetration, SC 6 (300/400 penetration), and SC 3,000 (SC 5). With the exception of Figures 10, 11, 12, and 13, which were taken in 1965 when the pavements illustrated were four years old, all pictures were taken in 1967.

Figures 5 to 9 are of pavements on the Trans-Canada Highway in Northern Ontario. Figure 5 shows the serious transverse cracking in a pavement made with 85/100 penetration asphalt located about 120 miles east of Port Arthur, and constructed in 1961. Figure 6 illustrates the near absence of transverse cracking in the adjacent pavement containing 150/200 penetration asphalt, constructed in 1960, and located about 110 miles east of Port Arthur.

Figure 7 indicates the numerous transverse cracks in an 85/100 penetration pavement constructed on the Trans-Canada Highway about 10 miles north of Sault Ste. Marie in 1960. Figures 8 and 9 illustrate the almost complete absence of transverse cracks in 150/200 penetration pavements constructed in the same highway in 1962 and 1963 respectively, about 30 miles and 40 miles north of Sault Ste. Marie.

Figures 10, 11, and 12 show the performance of a pavement after four years of service on a highway over a clay loam subgrade in Southern Ontario where the freezing index is about 1,000. All of the paving mixture for this project was made with the same aggregate and went through the same mixing plant. The only variable is the hardness of the asphalt cement. The asphalt binder is 85/100 penetration for several miles of pavement, but is 150/200 penetration for the remainder of the nine-mile project. Both asphalt cements were from the same crude oil source. Figure 10 illustrates the very obvious transverse cracking of the pavement containing 85/100 penetration asphalt. Figure 11 demonstrates the complete absence of transverse cracking in the immediately adjacent section of pavement on the same base and subgrade but containing 150/200 penetration asphalt. In Figure 12, pavement in the right hand lane contains 85/100 penetration asphalt, while that in the left lane is made with 150/200 penetration asphalt. The numerous transverse cracks in the 85/100 penetration pavement cross the centre line about 6 inches or so and then end in the 150/200 penetration pavement.

The pavement for Figures 10, 11, and 12 consists of a single lift two inches thick. About 40 miles away, the same 85/100 penetration asphalt cement that was used for the pavement of Figure 10 was employed at the same time for an asphalt pavement 5½ inches thick on a four-lane divided highway. Figure 13 illustrates its condition, also after four years. The near absence of transverse cracks in Figure 13 could be due to the stronger foundation normally provided for a four-lane highway, to the greater pavement thickness, to both, or to some unknown factor.

Winter pavement temperatures measured by Manz (13) for a pavement in Michigan indicated that the temperature was higher by from 4 to 6°F at a pavement depth of two inches as compared with that of the pavement surface, and was higher by from 16 to 19°F at a pavement depth of 5½ inches. A temperature difference of 16 to 19°F would result in a substantial difference between the contraction stresses acting at the surface of a pavement and at a depth of 5½ inches. The smaller resulting contraction strain of the lower portion of a pavement 5½ inches thick, would therefore act as a restraint to the tendency to cracking because of any lower temperature to which the pavement surface might be exposed. On the other hand, for an asphalt pavement only two inches thick, the temperature difference between the top and bottom half of the slab is small, and because of the absence of the restraint provided by the deeper portion of a thick pavement, the same low temperature could provide contraction stresses that could result in transverse cracking. These considerations, together with the obvious difference in performance of the thin and thick pavements of the same age shown in Figures 10 and 13, could be used as an argument for deep strength asphalt pavements to combat transverse cracking. These observations are supported by similar evidence from a limited number of other deep strength pavement projects.

Because during cold weather, higher temperatures are experienced with depth below a pavement surface, this implies that while softer asphalt cements may be required for the top layer or layers, harder asphalt cements might be specified for the deeper layers of a full depth asphalt pavement. This practice would take advantage of Monismith's (14) conclusion that harder asphalt cements provide greater fatigue resistance for thick asphalt pavements, and it has been pointed out elsewhere (15) that a higher modulus of stiffness for a paving mixture, which could be achieved by using harder asphalt cements, can result in a substantial reduction in the pavement thickness requirement.

Figures 14, 15, and 16 are pictures of Alberta pavements. Figure 14 illustrates numerous transverse cracks in a pavement containing 150/200 penetration asphalt that was constructed in 1963. Figure 15 demonstrates that transverse cracks extend across the paved shoulder when hot-mix pavement containing 150/200 or 200/300 penetration asphalt is used for paving the shoulder as well as the main pavement. On the other hand, Figure 16 shows that when the main pavement is made with 150/200 or 200/300 penetration asphalt, but the asphalt binder for the paved shoulder is MC 2 or MC 3, transverse cracks usually stop at the edge of the main pavement and the paved shoulder remains uncracked.

Figures 17, 18, 19, and 20 illustrate pavement performance in Saskatchewan. Figure 17 shows transverse cracking in pavement containing 150/200 penetration asphalt that was constructed in 1959. Figure 18 indicates the very noticeable bumps that develop at transverse cracks when the subgrade contains substantial amounts of montmorillonite clay. After the pavement cracks, water enters and passes down through the granular base into the subgrade. The subgrade swells for a distance of from nine to 12 inches on each side of the crack and causes a bump in the pavement at each crack. These bumps occur on some highways in Alberta, Saskatchewan, and Manitoba. At times the bumps are so pronounced that vehicles try to obtain a smoother ride by driving with the outside wheels on the paved shoulder where the bumps do not seem to develop. Figure 19 illustrates the well marked quite regularly spaced transverse cracks from 100 to 150 feet apart that have occurred in a pavement consisting of 16 inches of granular base and an asphalt surface treatment. On the other hand, Figure 20, taken just a few miles further on the same road, and over the same subgrade, shows none of these transverse cracks in a pavement consisting of ¾ inch of SC 2 road mix laid directly on the subgrade, a surfacing design that now paves about 5,000 miles of secondary roads in Saskatchewan.

Figures 21, 22, 23, 24, and 25 are pictures of asphalt surfaced main highways in Manitoba that are usually four inches thick. These pictures are particularly significant because they ilustrate the effect of a wide variation in the hardnes of the asphalt cement, ranging from 150/200 penetration to SC 3,000 (SC 5), on transverse pavement cracking, in the settled part of Canada with the highest freezing index. Figure 21 shows a 150/200 penetration pavement constructed in 1960, while Figure 22 is a picture of a 150/200 penetration pavement built in 1962. Numerous transverse cracks are readily apparent in both of these pavements, and they have reflected through a seal coat. Figure 23 illustrates a pavement constructed in 1952 with SC 6 asphalt binder (300/400 penetration asphalt cement). Although it is 15 years old, it contains very few transverse cracks. Figure 24 shows an SC 6 (300/400 penetration asphalt cement) pavement that is two years old and is nearly free from transverse cracks. This might not seem unusual except that 150/200 penetration pavements in Manitoba that are two years old have transverse cracks spaced from about 20 to about 50 feet apart. Figure 25 illustrates an SC 3,000 (SC 5) pavement that is two years old, and that has almost no transverse cracks.

Figures 14, 17, 21, and 22, illustrate the degree of transverse cracking that has developed in practically every asphalt pavement constructed in Alberta, Saskatchewan, and Manitoba with 150/200 or 200/300 penetration asphalt cement, that is more than two years old.

4. Discussion of Photographic Evidence

Table 1 contains inspection data on the composition of the paving mixtures illustrated in Figures 5 to 25. The paving mixtures are made with aggregates from nearby gravel pits which are ordinarily crushed to pass a ¾ inch screen. The aggregates are usually separated into two sizes by a ¼ inch screen before mixing with hot asphalt cement. They are laid on well compacted granular bases with mechanical spreaders, and are compacted by steel-wheel rollers, often supplemented with pneumatic-tire rollers.

Table 2 contains the limited inspection data that are available on the original asphalt cements employed for the paving mixtures shown in Figures 5 to 25. These include 85/100 penetration, 150/200 penetration, SC 6 (300/400 penetration), and SC 3,000 (SC 5).

When Figures 14, 17, 21, and 22, illustrating typical pavements made with 150/200 penetration asphalt which have developed numerous transverse cracks in Alberta, Saskatchewan, and Manitoba, are compared with those shown in Figures 23, 24, and 25, which are Manitoba pavements containing SC 6 (300/400 penetration) and SC 3,000 (SC 5), and are relatively free, or completely free from transverse cracks, the beneficial influence of softer grades of asphalt cement in achieving a marked reduction in transverse cracking is clearly evident. The same conclusion is drawn when Figures 5, 7, and 10, showing Ontario pavements containing 85/100 penetration asphalt, are compared with Figures 6, 8, and 11, illustrating the performance of those made with 150/200 penetration asphalt.

It is apparent from Figures 5 to 25, that for pavements made with 150/200 penetration asphalt, transverse cracking is much more severe in Alberta, Saskatchewan and Manitoba, Figures 14, 17, 21, and 22, than in Ontario, Figures 6, 8, 9, and 11. Except possibly for the warmer areas of southwestern Alberta, the Prairie Provinces do not have older 150/200 penetration pavements as free from transverse cracks as those of Ontario shown in Figures 6, 8, 9, and 11. This could be due to two factors. First, as indicated by Figure 2, the freezing index for the portion of the Trans-Canada Highway in Ontario on the northern fringes of the Great Lakes is from about 2,000 to 2,500. On the other hand, for southern Manitoba, central Saskatchewan, and northern Alberta, the freezing index ranges from about 3,000 to 4,000. Secondly, the range of temperature fluctuation tends to be greater and more frequent in the Prairie Provinces because of the Chinooks (warm winds from the Pacific) that occasionally move through the Rocky Mountains and over this region during the winter. They cause large temperature fluctuations in Alberta, which gradually become less pronounced as they move eastward over Saskatchewan and Manitoba. Consequently, these large and fairly frequent fluctuations in temperature subject pavements in the Prairie Provinces (Alberta, Saskatchewan, and Manitoba) to a greater number and range of repeated temperature stresses than in northern Ontario. Therefore, it should not be unexpected that the two factors of higher freezing index and greater and more frequent temperature fluctuations, could have a much more serious effect insofar as the development of transverse pavement cracking is concerned, on 150/200 penetration pavements in the Prairie Provinces, than occurs with 150/200 penetration pavements on the Trans-Canada Highway immediately north of the Great Lakes in Ontario.

While it might be expected that less pavement cracking would occur if a high asphalt content were used, field observations do not seem to support this conjecture. A number of sections of pavements that were even flushing or bleeding have been examined. If a hard grade of asphalt cement was used, pavement cracking appeared to be as severe and of the same pattern for flushed and bleeding sections as for those containing a more normal asphalt content. Furthermore, this observation appears to be supported by Hills and Brien (16) on the basis of laboratory tests they have conducted. Their studies showed no significant influence on fracture temperature (the temperature at which low temperature thermal stresses cause pavement cracking), when the asphalt content of the paving mixture was varied between 4.8 and 7.4 percent.

5. Results of Tests on Pavement Samples

Unfortunately in highway engineering, the evidence supporting certain conclusions is seldom absolute and clear cut. For a number of pavements on the Trans-Canada Highway north of the Great Lakes in Ontario, it appeared that there were approximately as many transverse cracks in pavements made with 150/200 penetration asphalt as in those containing 85/100 penetration asphalt. Through the courtesy of the Ontario Department of Highways, samples were cut from a number of these pavements. The samples were taken from the inner wheel path from pavements that were approximately three inches thick, and that had been laid in two layers, a binder and a surface course of the same paving mixture.

At the same time, a transverse crack count was made at each sample location over a length of 1,000 feet, 500 feet on each side of the sample site. As illustrated by Figure 26, four types of transverse cracks were recognized and counted. Type 1 cracks extended completely across the traffic lane. Type 2 cracks started at the outer edge but crossed the traffic lane only part way. Type 3 cracks started at the inner edge of the traffic lane but progressed only part way across the lane, while Type 4 cracks formed in the traffic lane but did not extend to either boundary of the lane.

The inspection data obtained by Mr. Lefebvre of our Research Department on the surface layer of these pavement samples are listed in Table 3, while the inspection data on the original asphalts and on the asphalt cements recovered from the surface layer of the pavement samples are given in Table 4.

Attempts were made to relate the transverse crack count to various properties of the recovered asphalt. No relationship could be established with a total number of cracks per 1,000 feet or per mile that included any combination of Types 1, 2, 3, and 4 cracks. However, as illustrated by Figures 27 and 28, useful information appears to result when the number of Type 1 cracks per 1,000 feet are plotted versus the penetration at 77°F, and the penetration at 32°F, respectively, of the recovered asphalts. For the area immediately north of the Great Lakes, Figure 27 appears to indicate that Type 1 transverse cracking is not serious as long as the penetration at 77°F of the recovered asphalt is higher than about 60. Figure 28 seems to show that Type 1 transverse cracking is minor when the penetration at 32°F of the recovered asphalt is not less than 20. It should be emphasized that for this region, to avoid transverse pavement cracking the recovered asphalt must satisfy **both** of these minimum penetration requirements, 60 penetration at 77°F, and 20 penetration at 32°F. It will be observed from Figures 27 and 28, that the five recovered asphalt cements that meet these criteria were originally all 150/200 asphalts.

There appears to be no difference in the ranges of age, percent passing No. 200 sieve, and percent air voids for the five pavement samples in Tables 3 and 4 that satisfy these penetration criteria, and for the 15 pavement samples that do not. However, Figures 27 and 28 indicate the need for employing every good design and construction technique for retarding the rate of hardening of the asphalt cement in service. In addition to starting with a softer grade of asphalt cement, these include designing for thicker asphalt films, low air voids, and requiring compaction by rolling to much higher density, and preferably to 100 percent of laboratory compacted density, during construction.

Table 5 provides inspection data on samples of 85/100 and 150/200 penetration pavements in Southern Ontario, that are illustrated in Figures 10, 11, and 12. Samples 1 and 2 are from the 85/100 penetration pavement shown in Figure 10, and in the right hand lane of Figure 12 respectively. Samples 3 and 4 are from 150/200 penetration pavement in the left hand lane of Figure 12 and from Figure 11 respectively. Inspection data on the asphalt cements recovered from these pavement samples together with transverse crack count information, are listed in Table 6. The penetrations at 77°F of the asphalt recovered from the two samples of 85/100 penetration pavement are 42 and 46, while for the two samples from the 150/200 penetration pavements they are 140 and 125. At 32°F, the penetrations of the two samples of 85/100 penetration pavement are 11 and 11, and for the two samples of 150/200 penetration pavement are 22 and 20. Consequently, the much greater softness of the asphalt cement recovered from the 150/200 penetration pavement, accounts for the obviously great difference between the severe transverse cracking of the 85/100 penetration pavement and the complete absence of transverse cracking in the 150/200 penetration pavement, that is illustrated in Figures 10, 11, and 12.

Table 7 contains inspection data for 10 samples from Manitoba pavements provided through the courtesy of the Manitoba Department of Highways, that are particularly informative because they represent pavements that were made with 150/200 penetration, SC 6 (300/400 penetration), and SC 3,000 (SC 5) asphalt cements. Table 8 lists inspection data on the asphalt cements recovered from the four 150/200 penetration pavements, samples 1, 4, 6, and 10, that range in age from three to eight years, are 60, 81, 61, and 78, and the corresponding penetrations at 32°F are 13, 16, 18, and 19. For the high freezing indices of Southern Manitoba, which range from 3,000 to 4,000, these recovered asphalts are much too hard, and they result in the severe transverse pavement cracking that is observed in Figures 21 and 22. Although samples 2 and 3 were obtained from SC 6 pavements that are 16 and 17 years old, the penetrations at 77°F of the recovered asphalts are 160 and 133, and at 32°F they are 51 and 43. Because the recovered asphalt cements are still soft, almost no transverse cracking has occurred, Figure 23. This is also true of the SC 6 pavement represented by sample 5, Figure 24, for which the penetrations at 77°F and at 32°F of the recovered asphalt are 143, and 34 respectively, although it is only three years old. Samples 7, 8, and 9 represent SC 3,000 (SC 5) pavements that are three years old, Figure 25. The penetrations at 77°F of the asphalt cements recovered from these pavements are 339, 374, and 320, and at 32°F they are 92, 95, and 102. Because these asphalt cements are still very soft, little or no transverse pavement cracking has developed, Figure 25. Consequently, Figures 21 to 25 and Tables 7 and 8, demonstrate the effectiveness of soft asphalt cements for dramatically reducing transverse pavement cracking.

Attention is directed to the relatively high asphalt absorption values of the aggregates in nine out of ten pavement samples reported in Table 7. Gravel deposits in Southwestern Manitoba from where these pavement samples were taken tend to be quite high in shale content. For eight out of the ten samples, the asphalt absorption values range from 1.0 to 1.5 percent, while for another sample it attained a value of 1.96 percent. These high asphalt absorption values reduce the effective asphalt contents in the pavements represented by these samples to between three and four percent for seven out of the ten samples. This results in quite thin asphalt coatings which could be expected to harden rather rapidly in service. This in turn could lead to earlier pavement cracking, even with soft asphalt cements, than would ordinarily be anticipated.

Figure 29 illustrates the relationship between penetration values at 32°F versus ductility values at 39.2°F for the recovered asphalts from the samples of 85/100 and 150/200 penetration pavements listed in Tables 4, 6, 8 and 12. Figure 29 tends to show a reasonably orderly correlation between these two variables. A plot of ductility values at 39.2°F versus penetration values at 77°F provides a similar correlation. Consequently, there does not appear to be any special relationship between ductility at 39.2°F and Type 1 transverse pavement cracking, that is not illustrated more effectivly in terms of penetration at 77°F and penetration at 32°F versus transverse pavement cracking, Figures 27 and 28.

While not listed in Tables 4, 6, and 8, inspection data for penetration ratios for the original asphalts referred to would range from 20 to 35. However, Tables 4, 6, and 8 indicate that the penetration ratios for the recovered asphalts generally range from 30 to 45. This is the direction of change in penetration ratio that would be expected if the original asphalt cements had been subjected to quite intensive oxidation.

Tables 4, 6, and 8 seem to indicate that when the number of Type 1 transverse pavement cracks is small, there are very few and even a general absence of transverse crack Types 2, 3, and 4. It may be that the latter three types of cracks are due more to fatigue than to thermal stresses.

Incidentally, Tables 3, 5, and 7 show that the in-place densities of the pavements represented by the samples range from 94.0 to 99.7 percent of 75-blow (60-blow Marshall mechanical compactor) Marshall density.

6. Influence of Pavement Foundation on Transverse Pavement Cracking

There is no doubt that the subgrade and granular base are responsible for some asphalt pavement transverse cracking. Nevertheless, in the pavements illustrated in Figures 5 to 25, and in many others, the numerous transverse cracks that occur in pavements containing the harder grades of asphalt cements are sharply reduced, or disappear altogether, when much softer asphalt cements are employed. This leads to the tentative conclusion that in Canada at least, the subgrade and granular base are much less responsible for the transverse pavement cracking that has been occurring than are the characteristics of the asphalt pavement itself.

It has long been recognized that pavements laid over the subgrades of relatively clean sand or gravel in cold climates, develop more numerous transverse cracks regardless of the softness of the asphalt cement, than pavements over clay subgrades. A possible explanation for this, that is not original with the author, is that the thin films of moisture on sand or gravel particles freeze at approximately 32°F. The moisture contents of most well drained sands and gravels are so low that when frozen they have very limited tensile strength. Consequently, during the contraction that accompanies decreasing temperatures below freezing, this weak tensile strength is soon exceeded, and transverse cracks develop in these subgrades at relatively close intervals. With clay soils on the other hand, only part of the moisture freezes at approximately 32°F, while the more tightly adsorbed moisture remains unfrozen. Consequently, at temperatures below freezing, a clay soil is not a rigid solid, but tends to remain somewhat plastic. As the temperature of the subgrade decreases below freezing creating contraction stresses, a clay soil, being more plastic, can stretch as required, and transverse crack formation is therefore much less frequent.

This leads to the possibility that the thick granular bases employed for conventional asphalt pavements may be functioning in part like subgrades of sand or gravel, and may contribute substantially to whatever transverse pavement cracking develops. This possibility is supported by a comparison of Figures 19 and 20 illustrating pavement performance in Saskatchewan, southeast from Regina. The pavement in Figure 19 consists of 16 inches of granular base with a thin asphalt surface treatment, placed over a heavy clay subgrade. The well marked transverse cracks located every 100 to 150 feet are clearly discernible. The pavement in Figure 20 consists of ¾ inch of SC 2 road mix laid directly on the same heavy subgrade as that for Figure 19. No transverse cracks like those of Figure 19 are to be seen in Figure 20. This suggests that the cause of the transverse cracking in Figure 19 may be the thick granular base under the surface treatment. If this should be the case, it suggests further that by eliminating the thick granular bases of conventional asphalt pavements, and substituting properly designed asphalt treated bases, transverse pavement cracking might be greatly decreased. This is also indicated tentatively by a comparison of the serious transverse pavement cracking in the 2-inch 85/100 penetration pavement of Figure 10 with the absence of transverse cracking in the 5½ inch asphalt pavement of Figure 13, which contains the same 85/100 penetration asphalt cement, and is of the same age.

7. Useful Information on Transverse Pavement Cracking Provided by Test Roads in Saskatchewan and Ontario

Figure 30 provides a comparison between grades of asphalt cement that would be obtained by grading by viscosity at 140°F, to give grades AC 3, AC 6, AC 12, AC 24, and AC 48, as proposed recently, versus the current grading of asphalt cements by penetration at 77°F. Figure 30 indicates the relationship between viscosity at 140°F versus penetration at 77°F for asphalt cements currently available in Canada, and it would also apply to much of the United States. The penetration indices (PI) values of 0.0, -1.0, and -1.5 indicated in Figure 30 for Lines A, B, and C, respectively, are similar to those developed by Pfeiffer and Van Doormaal (17), and are measures of the temperature susceptibilities of asphalt cements. The method employed in this paper to determine the penetration index (PI) of an asphalt cement, that can be related to transverse pavement cracking in Canada, is outlined in a later section of this paper.

For the 150/200 penetration grade of asphalt cement, which has been widely used by highway departments in Western Canada, Figure 30 demonstrates that depending on crude oil source, its maximum viscosity at 140°F can be about three times its minimum viscosity at 140°F. The corresponding range of penetration index (PI) is from 0.0 to -1.5, respectively. The Saskatchewan Department of Highways recently investigated the influence of wide range viscosity at 140°F **for the 150/200 penetration grade,** on the degree of transverse cracking that would develop in pavements. Randomized test pavements containing five different 150/200 penetration asphalt cements ranging in viscosity at 140°F from 350 to 811 poises were constructed in 1963. Each test section was 1,000 feet in length and consisted of one pavement layer of two inches compacted thickness laid on a primed granular base. Typical inspection data for these paving mixtures are listed in Table 9. A very informative detailed report by Culley (18) on this test project was released in 1966, based on the amount of transverse cracking that had been observed **after two years of service.**

Figure 33 has been prepared from data contained in this report. It indicates that **for the 150/200 penetration grade,** there is noticeably less transverse cracking for high viscosity (high penetration index, PI), average crack spacing 46 feet, than for low viscosity (low penetration index, PI), asphalt cements, average crack spacing of 24 feet. While it might seem that 150/200 penetration asphalt cements with a higher viscosity at 140°F than 811 poises would lead to still less transverse cracking, reference to Figure 30 will indicate that such asphalt cements are not presently available in Canada.

It should be emphasized in connection with Figure 33, that no highway engineer is going to be satisfied with pavements that develop transverse cracks every 46 feet after only two years of service. Consequently, in the Canadian Prairie Provinces, specifying 150/200 penetration asphalt with even the highest viscosity at 140°F that is available, is not a satisfactory answer to the transverse pavement cracking problem. On the other hand, Figures 23, 24, and 25, and the experience of the Manitoba Department of Highways, indicate that one very practical answer to the problem of transverse pavement cracking is the use of softer grades of asphalt cement, 300/400 penetration, SC 3,000 (SC 5), and even SC 800 (SC 4).

For the 85/100 penetration grade, Figure 30 demonstrates that its maximum viscosity at 140°F (PI = 0.0) is about four times its minimum viscosity at 140°F (PI = -1.5). In 1960, the Ontario Department of Highways constructed **three** asphalt paved Test Roads, each six miles in length, to compare the long term performance of pavements made with 85/100 penetration asphalts which had high, intermediate, and low viscosities at 140°F. In each six-mile Test Road, two miles were paved using 85/100 penetration high viscosity (high PI) asphalt cement from one supplier, two miles were paved using 85/100 penetration intermediate viscosity (intermediate PI) asphalt cement from another supplier, and two miles were paved using 85/100 penetration low viscosity (low PI) asphalt cement provided by a third supplier. Inspection data on samples of each of the three 85/100 penetration asphalt cements employed in these Test Roads are listed in Table 10. The three Test Roads were located in Southwestern Ontario near Galt, London, and about 40 miles east of Sarnia, and were about 40 miles apart. The three test sections in each Test Road were paved by one contractor using a single aggregate source. However, a different aggregate source was used for each Test Road. For each test section the asphalt pavement was three inches thick, and consisted of a binder course and a surface course laid on a compacted granular base. The underlying subgrade in each case was a clay loam.

A crack survey was made on each of the three test pavements in each of the three Test Roads this fall (1968) when they were eight years old. Through the courtesy of the Ontario Department of Highways pavement samples were obtained from each of the nine test sections on the three Test Roads, and they were analyzed by Mr. Lefebvre of our Research Department. Results of the analyses of the pavement samples are given in Table 11, while the crack survey count, and inspection data on the asphalt cements recovered from the surface courses, are listed in Table 12.

The following comments are made on the data in Table 12, and are illustrated graphically in Figures 34, 35, 36, and 37:

1. Although the asphalt cements in these nine test sections were originally 85/100 penetration, Table 12 shows that after eight years of service they have in general hardened to 30/40 penetration.

2. Table 12 and Figure 34 demonstrate that in addition to hardening, the penetration index (PI) of each of the three asphalt cements has increased substantially during eight years of service. That is, their temperature susceptibility has decreased. Table 12 and Figure 34 also indicate that the penetration index (PI) of the asphalt cement provided by Supplier 2 has increased much more in service than that of either of the other two Suppliers.

3. Figure 35 illustrates a plot of the number of Type I transverse cracks per mile versus the penetration indices (PI) of the **original** 85/100 penetration asphalt cements that are listed in Table 12. For each of the three Test Roads, Figure 35 demonstrates that the number of cracks per mile increases as the penetration index (PI), or viscosity at 140°F, of the **original** asphalt decreases. This agrees with Saskatchewan experience as illustrated in Figure 33. Figure 35 is also supported by observations of transverse pavement cracking in general in Canada, which have shown that **for any given penetration grade,** the amount of transverse cracking increases as the penetration index (PI) of the **original** asphalt cement decreases.

4. In Figure 36, the number of Type I cracks per mile has been plotted versus the penetration indices (PI) of the **recovered** asphalt cements. Although for all three Test Roads, the **recovered** asphalt provided initially by Supplier 2 has the highest penetration index (PI), pavements containing it do not have the least number of cracks per mile.

5. Figures 35 and 36 demonstrate clearly that for the normal construction conditions and environment associated with these three Test Roads, the number of transverse cracks per mile is related to the penetration indices (PI) of the **original** asphalt cements, not to those of the **recovered** asphalts. This would seem to question the wisdom of discarding requirements for the original asphalt cements, and of basing specifications for example in the thin film oven test residues.

6. Figure 37 is a plot of the number of Type I transverse cracks per mile versus the modulus of stiffness for slow loading (through chilling) at 0°F, calculated for each of the nine eight-year old pavements in the three Test Roads. The calculated values for moduli of stiffness were based on data in Tables 11 and 12, and involved the use of Figures 42, 44, and 45. Figure 37 appears to indicate that the number of transverse cracks per mile is related to the modulus of stiffness of the paving mixture when chilled to its minimum temperature on the road. When all other factors are equal, the higher this modulus of stiffness value for the paving mixture, the greater is the number of transverse cracks per mile.

7. Figure 35 implies for pavements made with 85/100 penetration asphalt cements over the penetration index range of 0.0 to -1.5, Figure 30, that **after eight years of service** the number of transverse cracks in a pavement containing a low viscosity asphalt cement (penetration index of -1.5) ranges from 20 to 50 times as many as the number of transverse cracks in a pavement made with a high viscosity asphalt cement (penetration index approaching 0.0).

8. For pavements made with the asphalt cement provided by each of the three suppliers, Figure 35 indicates that the number of Type I cracks per mile after eight years of service, varies very widely between these three Test Roads. For Supplier 2 for example, there are 19, 8 and 2 cracks per mile for Test Roads 1, 2, and 3, respectively. This indicates that differences in factors such as aggregate, design and construction

practice, foundation, and environment, contribute to transverse cracking as well as the hardness and characteristics of the asphalt cement. Nevertheless, on any one of these three Test Roads, there is a greater variation in transverse cracking based on differences in the penetration index (PI) of the three asphalt cements employed, for example 3, 8, and 62 cracks per mile in Test Road 2 for asphalt cements provided by Suppliers 1, 2, and 3 respectively, than there is between the three Test Roads on the basis of the asphalt cement from any single supplier. This seems to indicate that the hardness and other characteristics of the original asphalt cement employed for asphalt concrete, is the most important single factor contributing to low temperature pavement cracking.

9. Figure 35 demonstrates that in southwestern Ontario, any asphalt cement such as the 85/100 penetration asphalt cements that were used in the three Test Roads, which hardens in service to 30/40 penetration, can be expected to lead to at least some low temperature transverse pavement cracking.

10. Another nine-mile Test Road in the same general area, Figures 10, 11 and 12, was paved in 1961 with a 2-inch layer containing low viscosity, low penetration index (PI = -1.64), asphalt cements of 85/100 and 150/200 penetration, both from the same crude oil source. The 85/100 penetration asphalt was the same as that provided by Supplier 3 for the three Test Roads referred to in Figures 34, 35, 36, and 37. After six years of service, a transverse crack survey was made on representative portions of the pavement made with each asphalt cement. Point A in Figures 35 and 36 indicates more transverse cracks per mile after six years for the 85/100 penetration section than occurred on any of the other three Test Roads after eight years of service. A contributing factor to this could be the two-inch pavement of this nine mile Test Road, Figure 10, versus the three-inch pavement that was standard for the three Test Roads of Figures 34 to 37, since thinner pavements appear to develop more low temperature transverse cracks than thicker pavements. In spite of this, no transverse cracks of any kind occurred in the 150/200 penetration section, Figure 11 and the left lane of Figure 12. That is, there were less transverse cracks (actually no transverse cracking) in the pavement containing the low viscosity or low PI (PI = -1.64) 150/200 penetration asphalt, than occurred in any test section made with 85/100 penetration asphalt with the highest viscosity or highest PI provided by Supplier 1 for the three Test Roads, Figures 34 to 37.

11. This suggests that the increase in low temperature transverse cracking is not due to some particular physical or chemical component in the low viscosity (low PI) 85/100 penetration asphalt cement provided by Supplier 3 for the Three Test Roads, Figures 35 and 36, but is due primarily to the greater low temperature hardness (higher modulus of stiffness, Figure 37) of the pavement containing it. When a softer low PI 150/200 penetration asphalt cement was provided from the same crude by Supplier 3, which resulted in a much softer (lower modulus of stiffness) pavement at low temperature, no transverse cracking occurred.

12. This implies further, the importance of using soft asphalt cements to eliminate or greatly reduce transverse pavement cracking due to low temperature stresses. However, in addition to employing a soft asphalt cement, paving mixture design and construction practices must be modified to ensure that the asphalt cement remains soft in service, or at least hardens very slowly.

8. Need for Jumping Over One or Two Grades to a Softer Grade of Asphalt Cement to Substantially Reduce Transverse Cracking

Figures 5 to 9 demonstrate the very marked reduction in the transverse cracking of pavements that can occur in northern Ontario, when 150/200 penetration is used instead of 85/100 penetration asphalt. From Figure 30, the relatively large gap between 85/100 and 150/200 penetration can be seen. In going from 85/100 penetration to 150/200 penetration, two intervening grades 100/120 and 120/150 penetration have been jumped over.

In the Prairie Provinces recently, an attempt has been made to reduce transverse pavement cracking by changing from 150/200 penetration to 200/300 penetration. The results have been disappointing. The 200/300 penetration grade as ordinarily supplied, is not sufficiently softer than the 150/200 penetration to result in any substantial reduction in transverse cracking. Consequently, before the Prairie Provinces can expect any real improvement in transverse pavement cracking, the evidence elsewhere and in the Province of Manitoba appears to indicate the need to jump over one or two grades, and to change from 150/200 penetration to 300/400 penetration, to SC 3,000 (SC 5) and even to SC 800 (SC 4). Manitoba has already moved tentatively in this direction, and has constructed with success several SC 3,000 (SC 5) pavements during the past three years, Figure 25. In 1968, the Ontario Department of Highways has constructed a number of 300/400 penetration pavements in northern Ontario, and Alberta has constructed one long paving job with SC 3,000 (SC 5).

It will be seen later, for example Figure 47, that when changing to a softer grade of asphalt cement, the temperature susceptibilities of the two asphalt cements should be taken into account. A marked improvement in severe transverse pavement cracking could normally be expected by changing to the next softer grade of asphalt cement provided it has a substantially lower temperature susceptibility (substantially higher penetration index). Nevertheless, when the asphalt cements come from a single crude oil source, to greatly reduce or eliminate serious transverse pavement cracking, it is necessary to jump over at least one, and preferably over two grades in the direction of softer asphalt cements.

9. Wide Differences in Viscosity at 140°F for Harder Asphalts Are Much Less for Softer Grades

Figure 30 shows that for any given penetration at 77°F, Lines A and B representing the maximum and minimum viscosities at 140°F of Canadian paving asphalts, converge toward the lower right. For example, the large differences in viscosity at 140°F for the harder paving grades, 800 to 3,600 poises for the 60/70 penetration grade, and 500 to 2,000 poises for the 85/100 penetration grade, become only 100 to 300 poises for the 300/400 penetration grade. Consequently, differences in viscosity of asphalt cements due to crude oil source, become less and less progressively softer grades of asphalt cement. For all liquid asphalt grades, for example, SC 3,000 (SC 5) or SC 800 (SC 4), the accepted maximum viscosity limit has always been twice the minimum limit of viscosity. Therefore, including a viscosity requirement in specifications for 300/400 penetration and softer penetration grades of asphalt cements may be of little practical significance.

10. Danger From Specifying SC 6 Asphalt

Depending upon crude oil source, Figure 30 shows that the SC 6 grade, which has been widely used in Canada and in the western USA, includes asphalt cements ranging from 150/200 to 600 penetration at 77°F. Figures

21 to 24 demonstrate that in the Prairie Provinces severe transverse cracking occurs when 150/200 penetration asphalt is used, whereas much less transverse cracking develops even when 300/400 penetration asphalt cement is employed. Therefore, since the SC 6 specification includes within its corresponding range of penetration at 77°F harder grades of asphalt cement (150/200 penetration) that can result in severe transverse pavement cracking as well as softer grades of asphalt cement (500/600 penetration) that develop very little or no transverse cracking, any existing specification for the SC 6 grade should be discarded. It should be replaced by a specification for 300/400 penetration asphalt cement.

11. Possible Need for Special Specifications for SC 3,000 (SC 5) and SC 800 (SC 4) to Reduce or Eliminate Transverse Cracking

Figure 30 indicates that for the SC 3,000 (SC 5) liquid asphalt grade, the corresponding range of penetration at 77°F is from 500 to 1,500. Similarly, for the SC 800 (SC 4) grade, the parallel penetration range at 77°F is from 1,500 to 3,500. The correlation between viscosity at 140°F and penetration at 77°F shown in Figure 30 has been obtained by extrapolating Lines A and B. Actual penetrations at 77°F for SC 3,000 and SC 800 liquid asphalt grades could be measured by using a penetration needle six inches or more in length as has been employed by Lewis and Welborn (19).

SC 3,000 and SC 800 are often manufactured by blending a harder asphalt cement with a substantial amount of a heavy distillate solvent. Present specifications for SC 3,000 permit up to 5 percent of distillate recoverable at 680°F, while up to 12 percent of distillate recoverable at 680°F is permitted for SC 800. With these quantities of even a heavy distillate, SC 3,000 or SC 800 may harden substantially in service due to loss of distillate, leaving a relatively hard asphalt cement. Consequently, while the use of currently produced SC 3,000 or SC 800 might lead to a marked reduction or even to the complete elimination of transverse cracking in the earlier years of a pavement, numerous cracks might develop during its later service life. Available evidence is not sufficient to indicate whether or not this result will occur. However, if it should happen, special specifications for SC 3,000 and SC 800 may become necessary, in which the stipulated amount of distillate recovered at 680°F is limited either to nil or to some value much below that permitted by current specifications for these grades.

12. Transverse Cracking In Cold Weather Versus Adequate Stability in Hot Weather

It is recognized that asphalt pavements should provide satisfactory performance under two extreme temperature conditions. They should be designed and constructed to avoid transverse cracking and other detrimental behavior under low winter temperatures, and they should develop adequate stability under high summer temperatures.

If softer grades of asphalt cement are required to avoid transverse pavement cracking in cold weather, their use will ordinarily provide pavements with less stability in hot weather than is obtained when harder grades of asphalt cement are employed, Figure 38. The need for adequate stability in hot weather will usually dictate the degree to which the asphalt cement can be softened in order to achieve better cold weather pavement performance.

Nevertheless, the experience of the Manitoba Department of Highways indicates that SC 3,000 (SC 5) paving mixtures laid on highways in Manitoba appear to have quite adequate stability for that province's hot weather traffic. For a number of years, 150/200 penetration asphalt has been the hardest asphalt cement used by the City of Edmonton, Alberta, for paving city streets, with no evidence of pavement instability. Winnipeg, Manitoba, is currently experimenting with a change from 100/120 penetration to 150/200 penetration asphalt for pavements for its city streets.

Figure 38 illustrates for two paving mixtures, the influence of degree of compaction on the corresponding Marshall stabilities that are developed. Both paving mixtures are identical, except that one contains 60/70 penetration asphalt cement, while the other is made with 150/200 penetration asphalt.

Ordinarily, the Marshall stability for 100 percent of laboratory compacted density which usually corresponds to the ultimate density attained under traffic, is the only stability value reported by a laboratory for a paving mixture it has designed. For example, Figure 38 shows that at 100 percent of laboratory compacted density, the Marshall stability of the paving mixture containing 60/70 penetration asphalt cement is 1,750 pounds.

However, many specifications at the present time require compaction by rolling during construction to only 95 percent of laboratory compacted density. Figure 38 illustrates a general finding (29), that pavements that have been rolled during construction to 95 percent of laboratory compacted density have only about 20 percent of their stability at 100 percent of laboratory compacted density. Consequently, when the paving mixture in Figure 38 containing 60/70 penetration asphalt is compacted to 95 percent of laboratory compacted density, its Marshall stability is only about 400 pounds. This is equal to the Marshall stability of the 150/200 penetration mixture when compacted to 97 percent of laboratory compacted density. Field experience appears to demonstrate that the low Marshall stability of 400 pounds for the 60/70 penetration paving mixture at 95 percent of laboratory compacted density provides quite adequate load carrying capacity for high volume heavy duty highway or city traffic. Furthermore, this low stability immediately after construction continues for several months, since it ordinarily appears to require from two to four years of traffic to gradually compact a pavement to 100 percent of laboratory compacted density.

In earlier papers (15, 21), the author has pointed out the merits of compacting pavements by rolling **during construction** to at least 100 percent of laboratory compacted density. It was shown that this density could probably be achieved during construction by the use of variable tire pressure pneumatic-tire rollers equipped with automatically controlled tire inflation pressure, Figure 39. From Figure 38, it can be seen that the paving mixture made with a soft asphalt cement (150/200 penetration) but compacted to 100 percent of laboratory compacted density, has a very much higher Marshall stability than the same paving mixture containing a harder asphalt cement (60/70 penetration) but compacted to only 95 percent of laboratory compacted density.

Consequently, the principal purpose of specifying a high Marshall stability in many current specifications, would appear to be to ensure that 20 percent of this stability value, corresponding to 95 percent of laboratory compacted density, will be adequate for anticipated wheel loads and traffic volumes. If paving mixtures are designed to satisfy Asphalt Institute criteria for VMA and air voids, and if they are thoroughly compacted during construction, there is considerable evidence that paving mixtures with substantially lower Marshall stabilities than current specifications often permit, will have satisfactory hot weather stability under traffic. Nevertheless, just how soft an asphalt cement can be selected to minimize transverse cracking in cold weather, and to provide at the same time adequate stability for traffic in hot weather, will be a matter for sound engineering experience and judgment in each region to decide.

13. Practical Construction and Pavement Performance Problems Imposed by the Adoption of Softer Asphalt Cements

If softer grades of asphalt cement are adopted to reduce or eliminate the transverse cracking of asphalt pavements, this could result in two very practical problems:

(a) delayed rolling behind the spreader when using current steel-wheel rollers, because of softness of the paving mixture at high temperatures, and

(b) rapid densification of the pavement by traffic to 100 percent of laboratory compacted density, which could lead to flushing or bleeding within a few months after construction, unless the paving mixture is properly designed.

It has been pointed out elsewhere (15, 21), that the first of these two problems, delayed rolling, can be handled most easily by employing pneumatic-tire rollers with rapidly adjustable (manually or automatically controlled) tire inflation pressure, Figure 39. By operating these rollers at a sufficiently low tire inflation pressure, the rollers can be kept right up to the spreader even when laying very soft paving mixtures, and the problem of delayed rolling does not exist.

The second of these two problems occurs because pavements containing softer asphalt cements offer less resistance to compaction, and therefore densify more rapidly under traffic following construction. This problem can be solved very simply by carefully designing surface course mixtures to satisfy Asphalt Institute air voids criteria, 3 to 5 percent air voids at 100 percent of laboratory compacted density.

14. Practical and Economic Advantages from Employing Soft Asphalt Cements to Reduce or Eliminate Transverse Cracking

It is recognized that changing to soft asphalt cements cannot be expected to always completely eliminate transverse pavement cracking, since it may be due to other causes than the use of asphalt cements that are too hard. Nevertheless, Canadian experience indicates that this simple change will usually be found to provide the most impressive reduction in transverse pavement cracking that can be made at little or no increase in pavement cost.

Some of the practical advantages resulting from the reduction or elimination of transverse pavement cracking by using softer asphalt cements are the following:

(a) Provides a paved surface with a much more attractive appearance.

(b) Provides longer pavement life.

(c) Preserves the integrity of the pavement structure.

(d) Maintains the paved surface in a smooth riding condition for a longer period.

Some of the economic advantages that result from the use of softer asphalt cements to reduce or eliminate transverse pavement cracking are as follows:

(a) Little or no increase in initial pavement cost. Most proposed solutions to serious road building problems require the additional expenditure of large sums of money. However, softer asphalt cements should ordinarily be little or no more expensive than harder asphalt cements. Consequently, it is a major advantage of the use of softer asphalt cements to control the transverse pavement cracking problem, that they can be utilized at little or no increase in the initial cost of the asphalt pavement.

(b) Reduced maintenance cost. There will be a substantial annual savings in the maintenance cost of filling from 100 to 300 or more cracks per mile per year.

15. Relationship to Early Asphalt Institute Study

In the 1930's, after reviewing the problem of pavement cracking in the central Mid-West and central Atlantic Coast areas of the United States, The Asphalt Institute (22) concluded that the cracking of asphalt pavements was either imminent or incipient when the asphalt cement had hardened to 30 penetration at 77°F, and was almost certain to occur when the asphalt cement had hardened to 20 penetration.

An immediate result of these published findings was a change to softer grades of asphalt cement in most areas.

The present investigation of transverse pavement cracking in Canada also associates pavement cracking with the hardness of the asphalt cement being used. In a sense therefore, the results of the present study extend the conclusions of the earlier Asphalt Institute enquiry into a colder area. Consequently, it should not be suprising that the findings of the current investigation also indicate the need for using softer grades of asphalt cement than those that are presently employed in Canada, if low temperature pavement cracking is to be greatly reduced or entirely eliminated.

Figures 27 and 28 indicate that for the region immediately north of the Great Lakes, transverse pavement cracking can be expected to become serious when the asphalt cement in a pavement has hardened to a penetration at 77°F of 60, and to a penetration at 32°F of 20. Consequently, in this region, in addition to emphasizing good design and construction practice, consideration of Figures 27 and 28 would seem to indicate that 300/400 penetration asphalt cement, and more likely SC 3,000 (SC 5), is the hardest grade that should be specified. In Alberta, Saskatchewan, and Manitoba, and in northern British Columbia, northern Ontario, and northern Quebec, where freezing conditions are more severe, and the freezing index is considerably higher, if transverse pavement cracking is to be avoided, the penetration of the asphalt cement in the pavement must always be substantially higher than 60 at 77°F, and than 20 at 32°F. Throughout this region in addition to good techniques for pavement design and construction, it would appear from Figures 21 to 25, that possibly 300/400 penetration, but more probably SC 3,000 (SC 5), and even SC 800 (SC 4) may be the hardest grade that can be used if serious transverse pavement cracking is to be overcome.

16. Theoretical Support for Use of Softer Asphalt Cements to Reduce Transverse Cracking

So far the evidence that softer asphalt cements can reduce transverse pavement cracking, has been based entirely on observations of pavement performance in the field as indicated by Figures 5 to 25, and on the analysis of pavement samples, Tables 3 to 12. It will now be shown that there is also a firm theoretical basis to support the conclusion that the use of softer asphalt cements can reduce and even eliminate transverse pavement cracking. This theoretical support is provided by investigations that have been conducted by Rader (23, 24, 25), by Van der Poel (26, 27), by Heukelom and Klomp (28) and by Hills and Brien (16).

Rader, when investigating asphalt pavement performance at low temperatures in the 1930's concluded that in order to resist low temperature cracking, asphalt pavements should have a low modulus of elasticity and a high modulus of rupture at these temperatures (23, 24, 25). He pointed out that when all other factors are held constant, the softer the asphalt cement, the lower the modulus of elasticity will be.

Figure 40 illustrates some conclusions by Hills and Brien (16) from a theoretical and laboratory study they made of fracture temperatures of pure asphalt cements and of paving mixtures. As the temperature is gradually lowered, developing thermal stresses and strains, the fracture temperature is the temperature at which the tensile stress exceeds the tensile strength, and a crack occurs. Using information developed by Heukelom (29), Hills and Brien (16) calculated the temperatures at which the tensile stresses developed by chilling either pure asphalt cements, or paving mixtures containing these asphalt cements, would exceed their corresponding tensile strengths. They checked their findings by means of low temperature laboratory tests, and found reasonably good agreement between the calculated and measured values for the temperatures at which fracture occurred. Figure 40 demonstrates that the harder the asphalt cement in terms of penetration at 77°F, the higher is the temperature at which pavement cracking can be expected. Furthermore, for asphalt cements of the same penetration at 77°F, but with different temperature susceptibilities, the fracture temperature of a paving mixture made with a less temperature susceptible asphalt (higher penetration index or PI), is lower than that for a similar mixture containing a more temperature susceptible asphalt (lower penetration index or PI). These conclusions by Hills and Brien are in qualitative agreement with the findings of this paper with respect to transverse pavement cracking under low temperature conditions in Canada.

It is worthwhile to examine the relationship between a pavement's modulus of elasticity at low temperature, and the tendency of the pavement to crack at low temperature. The following equation illustrates the relationship between stress, strain, and modulus of elasticity of an asphalt pavement, in conventional form:

$$E = \frac{\text{stress}}{\text{strain}} \qquad \text{.......... (1)}$$

where

E = modulus of elasticity

stress = measured in pounds per square inch

strain = measured as inches per inch of length

Equation (1) can be rearranged as:

$$\text{stress} = E\ (\text{strain}) \qquad \text{.......... (2)}$$

As a first approximation, for all similar dense graded asphalt concrete pavements, regardless of the asphalt cement they contain, it may be assumed that their coefficients of contraction, when their temperatures are decreased over a given range of low temperature, are identical (11). Consequently, it follows that the amount of strain (tendency towards shortening) set up in a given length of any asphalt pavement satisfying stipulated design and construction criteria, when its temperature is chilled over a given range in a specified time, is a constant (approximately). For these conditions therefore, Equation (2) can be rewritten as:

$$\text{stress} = E\ (\text{constant}) \qquad \text{.......... (3)}$$

Equation (3) indicates that the tensile stress induced in the pavement, when a given length of each of a series of similar pavements is cooled over the same temperature range in the same time period, varies directly with the moduli of elasticity of the pavements. Therefore, if the modulus of elasticity of one of these sections of pavement is high, the tensile stress induced in it as a result of chilling over a given temperature range in the specified time period will be high, and vice versa, if another section of pavement has a low modulus of elasticity, the induced tensile stress for the same conditions will be low, Equation (3).

It is axiomatic that when the induced tensile stress exceeds the tensile strength of a pavement, a pavement crack will be formed. Rader's investigation of low temperature pavement cracking indicated that this is most likely to occur when the modulus of elasticity of a pavement is high. This is confirmed by Figure 37 which is based on Ontario's three Test Roads. Figure 41, developed by Heukelom (29), indicates why this should be the case. Figure 41 shows that the tensile strain at which fracture occurs becomes rapidly less and less as the modulus of stiffness of a bitumen increases. Since the amount of strain that is developed in a given length of pavement when chilled over any specified temperature range in a given time is approximately constant regardless of the grade of asphalt cement it contains (approximately constant coefficient of contraction), Figure 41 indicates that pavement cracking is much more likely to occur when it contains a hard rather than a soft asphalt cement, that is an asphalt cement with a high rather than a low modulus of stiffness.

Rader's conclusions were based on an investigation of samples cut from pavements in service. Testing every paving mixture proposed for use to determine its modulus of elasticity could be somewhat time consuming. Even if this test can be made quite easily, engineers in general would like to have some guidance concerning the influence that any suggested change in paving mixture design is likely to have on its modulus of elasticity. Consequently, there is need for some reliable theoretical method that would enable an engineer to forecast in advance the moduli of elasticity to be expected for various asphalt paving mixtures. A theoretical method suitable for this purpose is provided by a nomograph developed originally by Van der Poel (26, 27), modified somewhat by Heukelom and Klomp (28), and slightly modified further by the author, Figure 42. This nomograph provides theoretical relationships between asphalt consistency and temperature susceptibility, temperature, rate of loading, and modulus of stiffness for asphalt cements. The modulus of stiffness of Figure 41 is equivalent to Rader's modulus of elasticity.

Before the nomograph of Figure 42 can be used to establish modulus of stiffness values for paving mixtures, the temperature susceptibilities of asphalt cements must be evaluated in terms of Pfeiffer's and Van Doormaal's (17) penetration index (PI), and a means for establishing the "base" temperature, which corresponds roughly to the softening point (ring and ball) of the asphalt cement, is required. While Pfeiffer and Van Doormaal list a range of PI from -5 to +10 for asphalts in general, Canadian paving asphalts (and probably most United States asphalts) appear to have a range of PI from 0 to -1.5, Figure 30. Figure 43 indicates diagrammatically that an asphalt cement with a PI of 0 has a higher viscosity at temperatures above 77°F, and a lower viscosity at temperatures below 77°F, than more temperature susceptible asphalts with a lower PI of -1.5. That is, the viscosity of an asphalt cement with a higher PI of 0 changes less with any given change in temperature than is the case with a more temperature susceptible asphalt with a PI of -1.5.

Pfeiffer and Van Doormaal (17) evaluated the penetration index (PI of an asphalt from an equation based on the softening point of the asphalt and its penetration at 77°F. For this purpose, it was assumed that the viscosity of any asphalt cement at its softening point is 12,000 poises. From an equation relating penetration and viscosity developed by Saal and Koens (30), it was assumed further that at its softening point the penetration of an asphalt cement was 800.

Table 13 prepared from data recently obtained by Lefebvre of our Research Department, shows for twelve commercial asphalts that the penetration of an asphalt cement at its softening point is seldom 800, and actually ranges at least from 630 to 4,500, and that its viscosity at the softening point instead of being 12,000 poises, ranges at least from 4,800 to 38,000 poises. Other investigators have shown similar large discrepancies (31).

Consequently, penetration index values when determined by Pfeiffer's and Van Doormaal's equation are quite often not realistic. This is also true of penetration index values based either on the actual penetration at the softening point, or on the temperature for 800 penetration, or on the temperature for 12,000 poises, Table 13. Unfortunately lack of space prevents any detailed discussion of Table 13.

Experience with Canadian asphalts has demonstrated that Newtonian viscosity at 140°F and penetration at 77°F, Figure 30, provide a much more reliable basis for establishing Pfeiffer's and Van Doormaal's penetration index than softening point and penetration at 77°F. Since penetration at 77°F is an approximate measure of viscosity at 77°F, Figure 30 tends to compare the viscosities of asphalt cements at 140°F and at 77°F, and therefore appears to indicate temperature susceptibility directly. For example, for asphalts 4 and 9 in Table 13, Pfeiffer's and Van Doormaal's equation gives very misleading penetration indices of +3.7 and +18.0 respectively, whereas the data of Figure 30 which is based on Newtonian viscosity at 140°F and penetration at 77°F, indicate the penetration indices to be -1.7 and -1.8 respectively, Table 10, which are much more realistic, and are in keeping with their service performance characteristics.

As a result of these considerations, the following steps are required to establish the penetration index (PI) of an asphalt cement, and its "base" temperature, both of which are needed to obtain a modulus of stiffness value for an asphalt cement from the nomograph of Figure 42.

1. By using,

   (a) the modification of Heukelom's (29) version of Pfeiffer's and Van Doormaal's chart that is illustrated in Figure 44,

   (b) the softening point (Ring and Ball), penetration at 77°F and Newtonian viscosity at 140°F, extrapolated if necessary from high temperature viscosity measurements, for appropriate "normal" asphalts,

   (c) and **the substitution of softening** point for "base" temperature in figure 44, obtain the best penetration index (PI) ratings of "normal" asphalts represented by the upper and lower boundaries, Lines A and B, of the chart of viscosity at 140°F versus penetration at 77°F illustrated in Figure 30. Inspection data indicate that "normal" paving asphalts, for at least the range from 30/40 to 150/200 penetration, have identical Pfeiffer and Van Doormaal penetration index values when they are obtained by vacuum reduction from the same crude oil, but have different PI values when they are obtained from different crudes. On this basis, the upper boundary of the chart of Figure 30, Line A, has a penetration index rating of 0.0, and the lower boundary, Line B, has a penetration index rating of -1.5. However, these penetration index ratings may be subject to some revision.

2. From the position of any given asphalt in terms of its penetration at 77°F and of its Newtonian viscosity at 140°F on the chart of Figure 30, its penetration index can be easily determined by means of simple ratio. For example, if its penetration at 77°F is 100, and its viscosity at 140°F is 1,000 poises, its penetration index is

   $$0.0 - \frac{(1850 - 1{,}000)}{(1850 - 460)}\,1.5 = 0.0 - 0.9 = -0.9$$

   The position for Line C, with a penetration index (PI) rating of -1.0, in Figure 30, was calculated on this basis.

3. From an asphalt cement's penetration index obtained in this manner from Figure 30, and the modification of Heukelom's chart illustrated in Figure 44, the asphalt cement's "base" temperature is roughly

similar to its softening point. It is sometimes the same, but depending on an asphalt cement's crude oil source it can be substantially different. The "base" temperature can be determined as illustrated in Figure 44. If the penetration of an asphalt cement at 77°F (25°C) is 80, and if its penetration index is 0.0, the temperature difference indicated by Figure 44 is 25°C and the base temperature is 25 + 25 = 50°C (122°F).

4. The bottom line in Figure 42 represents rate of loading. The middle line indicates service or other temperature relative to the "base" temperature of the asphalt cement, the horizontal lines at the top of the chart represent different values for the penetration indices of asphalt cements, while the curved lines at the top indicate different values for the moduli of stiffness of asphalt cements. The sample illustration on Figure 42 shows how easily the chart can be used to obtain values for moduli of stiffness of asphalt cements.

The procedure that has just been outlined for obtaining penetration indices and "base" temperatures for asphalt cements, is believed to be realistic, and it provides modulus of stiffness values for asphalt cements from Figure 42 that conform to Canadian experience with pavement performance.

Both Van der Poel (26, 27) and Heukelom and Klomp (28) have emphasized that their nomograph, Figure 42, is based on the characteristics of the asphalt cement recovered from the pavement after any particular period of service at which pavement performance is being investigated. However, to simplify the presentation in the balance of this paper, it is assumed that the asphalts recovered from the pavement are the original asphalt cements. This avoids uncertain speculation concerning the degree of hardening that has occurred that any reader is free to make for himself. In spite of this assumption, it is believed that the conclusions presented are generally in the proper relative order, particularly since Figures 35 and 36 indicate that the number of low temperature transverse cracks that develop in a pavement in service is related to the penetration index (PI) of the **original** asphalt cement, and not necessarily to the penetration index (PI) of the recovered asphalt.

Figure 45 has been plotted by using data taken from Figure 42. The range of penetration index values shown, 0.0 to -1.5, appear to correspond to the range of temperature susceptibility of paving asphalts presently being used in Canada, Figure 30.

Figure 45 shows a theoretical relationship between stiffness moduli for a rapid rate of loading at 122°F for six grades of asphalt cement 20/25, 40/50, 85/100, 150/200, 300/400 penetration, and SC 3,000 (SC 5), and for a PI range of 0.0 to -1.5 as the ordinate, versus the corresponding stiffness moduli for the same asphalt cements for a slow rate of loading at -10°F, as the abscissa. Because of some uncertainty concerning their exact positions, the locations of SC 3,000 (SC 5) and of 800/1,000 penetration asphalt are shown in Figure 45 as broken lines. The rapid rate of loading at 122°F, 50 cycles per second, corresponds to fast moving traffic at the highest effective Canadian pavement service temperature (13). The slow loading at -10°F approximates the rate at which low temperature thermal stresses are applied, $10^{4.3}$ seconds, as a pavement chills following a temperature change during a cold day or night. A time of loading of $10^{4.3}$ seconds is 20,000 seconds, or approximately six hours.

The modulus of stiffness values provided by Figures 42 and 45 are for pure asphalt cements. However, engineers are much more interested in modulus of stiffness values for asphalt paving mixtures made with these asphalt cements. Van der Poel (26, 27) and Heukelom and Klomp (28) have shown that for paving mixtures made to any specified design, there is a relationship between the modulus of stiffness values for these paving mixtures and the moduli of stiffness for the pure asphalt cements they contain. This relationship is illustrated in Figure 46 for paving mixtures all of which contain three (3) percent air voids.

In Figure 46, modulus of stiffness values for asphalt cements are given by the abscissa, and values for the moduli of stiffness for corresponding asphalt paving mixtures are listed on the ordinate axis. Various asphalt paving mixture designs are indicated by the curves of C_V values, where C_V is the ratio of the volume of aggregate in the paving mixture to the combined volumes of aggregate and asphalt cement, expressed as a decimal fraction. While Figure 46 pertains only to paving mixture designs for which the air voids content is three (3) percent, a method has recently been proposed (32) that enables charts similar to Figure 46 to be constructed, but for air voids values of more than three (3) percent. This method employs the following equation for this purpose:

$$C_V' = \frac{C_V}{1 + \triangle V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where C_V = volume of the aggregate expressed as a decimal fraction of the combined volume of aggregate plus asphalt cement in a paving mixture, when the volume of air voids in the paving mixture is three (3) percent.

C_V' = volume of the aggregate expressed as a decimal fraction of the combined volume of aggregate plus asphalt in a paving mixture, when the volume of air voids in the paving mixture is some value more than three (3) percent.

$\triangle V$ = difference, expressed as a decimal fraction, between the volume of air voids in a paving mixture, and an air voids value of three (3) percent. For example, if the volume of air voids in a compacted paving mixture is ten (10) percent, $\triangle V = 0.1 - 0.03 = 0.07$.

By means of Figure 46, for fast loading at 122°F (fast traffic), and for slow loading at -10°F low temperature thermal stresses), it is a simple matter to convert from the modulus of stiffness values of Figure 45 for pure asphalt cements, to the corresponding modulus of stiffness values for paving mixtures having an air voids value of three (3) percent, and for example, a C_V value of 0.88, Figure 47. These values for air voids and C_V represent dense graded asphalt concrete paving mixtures with either ⅝ inch or ¾ inch nominal maximum particle size, that satisfy Asphalt Institute paving mixture design requirements. The step by step procedure is as follows:

1. First of all, Figure 45 is prepared on the basis of modulus of stiffness values for the conditions of fast loading at 122°F and for slow loading at -10°F, for pure asphalt cements varying in penetration index (PI) from 0.0 to -1.5, and ranging in consistency from a penetration of 20 at 77°F to SC 3,000 (SC 5), by obtaining the required modulus of stiffness data from Figure 42.
2. For example, the modulus of stiffness for 100 penetration asphalt cement with a penetration index of 0.0 for slow loading at -10°F, is shown by Figure 45 to be 540 psi.
3. Enter the bottom of figure 46 at the value of 540 psi, proceed vertically upward to its intersection with the curved line labelled $C_V = 0.88$, and then horizontally to the left hand margin and read off the modulus of stiffness value for the corresponding paving mixture, 275,000 psi.

4. This provides the coordinate in Figure 47 for the modulus of stiffness of the paving mixture made with 100 penetration asphalt cement (PI = 0.0) for the condition of slow loading at -10°F. The other modulus of stiffness coordinate for the same paving mixture for fast loading at 122°F is similarly obtained, 70,000 psi.
5. The coordinates for all other points required to construct the chart of Figure 47 are obtained in the same manner. Figures 48, 49, 50, and 52, are similarly prepared.

Similar charts can be prepared for C_V values other than 0.88, and for air voids values of more than three (3) percent.

Incidentally, Figure 46 shows that if a bitumen with a low modulus of stiffness of say 1 psi (800 penetration, Figure 45), is combined with aggregate to give a paving mixture with a C_V value of 0.88, the modulus of stiffness of the resulting paving mixture at the same temperature and for the same rate of loading, is about 4,000 psi. That is, for this soft asphalt cement, the addition of mineral aggregate increases the modulus of stiffness about 4,000 times. On the other hand, if the bitumen itself has a modulus of stiffness of 10,000 psi (40/50 penetration, Figure 45), Figure 46 indicates that by mixing it with aggregate to obtain a paving mixture with a C_V value of 0.88, the modulus of stiffness of the paving mixture for the same conditions of temperature and rate of loading is about 1,500,000 psi, but the increase in modulus of stiffness due to the aggregate is only about 150-fold. Figure 46, therefore, indicates that the softer the asphalt binder, the greater is the increase in modulus of stiffness when it is combined with a given aggregate. This would seem to explain the suprisingly good performance of many road-mix pavements made with SC 250 (SC 2) or MC 250 (MC 2) liquid asphalts, for which the increase in modulus of stiffness due to the incorporation of the aggregate probably approaches or exceeds 10,000 times.

Figure 47 provides the theoretical basis for an engineer to estimate the moduli of stiffness to be expected for well designed paving mixtures containing asphalt cements ranging from 20/25 penetration at 77°F to SC 3,000 (SC 5), and varying in penetration index from 0.0 to -1.5, under fast traffic at 122°F as ordinate, and under the thermal stresses that develop when slowly chilling a pavement to -10°F as abscissa. Figure 47 will be reviewed first from the point of view of pavement performance under fast moving traffic at 122°F.

1. For paving mixtures containing asphalt cements of any given penetration at 77°F, for example 100 penetration, Figure 47 indicates that a paving mixture made with an asphalt cement with a PI of 0.0 would have a modulus of stiffness for fast loading at 122°F about 40 percent higher than if it contained an asphalt cement with a PI of -1.5, 70,000 versus 50,000 psi. Lefebvre (20) has shown that this would result in a difference in Marshall stability at 140°F of about 18 percent for the 85/100 penetration mixtures he investigated, in favour of the paving mixture made with asphalt cement with a PI of 0.0. These differences either in modulus of stiffness or in Marshall stability values due to variations in the penetration index (PI) of the asphalt binder from 0.0 to -1.5, do not seem to be reflected in observable differences in road performances in warm weather. In Canada at least, well designed and constructed asphalt pavements made with 85/100 penetration asphalt cements ranging in PI from 0.0 to -1.5, show no noticeable difference in service behaviour under hot weather traffic. This is also true of similar pavements containing 150/200 penetration asphalt cements having the same range of PI.
2. For the same penetration index for fast loading at 122°F, the modulus of stiffness of a paving mixture made with 100 penetration asphalt is about three and one-half times greater than when the same paving

mixture contains 400 penetration asphalt, 70,000 psi versus 20,000 psi for a PI of 0.0. This means that any given paving mixture made with 400 penetration asphalt tends to have substantially less stability under fast traffic at 122°F than when it contains 100 penetration asphalt, as would be expected. Nevertheless, experience of the Manitoba Department of Highways indicates that paving mixtures made with SC 3,000 (SC 5) asphalt binders, which are substantially softer than 400 penetration, appear to have adequate warm weather stability for Manitoba rural highway traffic and climatic conditions.

3. Some earlier investigators had reported that provided the viscosity at 140°F was the same, paving mixtures made with asphalt cements with a wide range of penetration at 77° had approximately the same Marshall stability at 140°F. Recent findings by Lefebvre (20) do not support this. Lefebvre (20, 4) showed that for paving mixtures made with asphalt cements having the same viscosity at 140°F (AC 12, Figure 30), that the paving mixture containing a 60/70 penetration low viscosity asphalt cement with a PI of about -1.5 had a Marshall stability at 140°F of 1450 pounds, while the same paving mixture but made with 150/200 penetration high viscosity asphalt with a PI approaching 0.0 had a Marshall stability of only 980 pounds. Figure 47 clearly supports Lefebvre's findings. For fast loading at 122°F, Figure 47 shows that the paving mixture containing 150/200 penetration asphalt with a PI of 0.0 (high viscosity) has a modulus of stiffness of about 45,000 psi , while 60/70 penetration asphalt with a PI of -1.5 (low viscosity) has a modulus of stiffness of approximately 75,000 psi.

Like its ordinate axis, the abscissa of Figure 47 is a logarithmic scale that indicates values of the modulus of stiffness induced in pavements when they are slowly chilled to -10°F. It can be seen from Figure 47 that under these conditions, the modulus of stiffness increases from about 2,000 psi for a pavement that contains SC 3,000 (SC 5) liquid asphalt to about 2,000,000 psi for a pavement containing 40/50 penetration asphalt, that is, a range in modulus of stiffness values of about 1,000-fold.

Rader (23, 24, 25) concluded that a low modulus of stiffness was essential if pavement cracking due to low temperature is to be avoided. The abscissa of Figure 47 makes it quite clear that the modulus of stiffness of an asphalt paving mixture at a low temperature, -10°F, varies directly with the degree of hardness of the asphalt cement it contains, and that to obtain a low modulus of stiffness for paving mixtures under these conditions, it is necessary to use a soft asphalt cement. Hills and Brien (16) also indicate, Figure 40, that to obtain a lower fracture temperature, that is to lower the temperature at which pavement cracking due to low temperature thermal stresses can be expected, a softer asphalt cement must be used.

Figure 35, which is based on results obtained on three Test Roads in Ontario in each of which three different 85/100 penetration asphalt cements were used, indicates that as the penetration index of the asphalt cement decreased from 0.0 to -1.5, the amount of transverse cracking increased by from about twenty to about fifty times. Figure 47 indicates that for paving mixtures containing 85/100 penetration asphalt cements with a range in PI from 0.0 to -1.5, the corresponding range in modulus of stiffness at -10°F is about four-fold, from 275,000 psi for a PI of 0.0 to 1,000,000 psi for a penetration index of -1.5. A comparison of Figures 35 and 37 with Figure 47 demonstrates that transverse cracking increases as the modulus of stiffness of the pavement increases. For a four-fold increase in modulus of stiffness, 275,000 psi to 1,000,000 psi, indicated by Figure 47 for pavements containing 85/100 penetration asphalt ranging in PI from 0.0 to -1.5, Figure 35 shows that the number of transverse cracks increased by from about 20-fold to about 50-fold after eight years of service.

The low temperature modulus of stiffness data of Figure 47 are in complete agreement with the observed transverse cracking of pavements at low temperatures in Canada. Increased low temperature pavement cracking is associated with the use of harder asphalt cements, which according to Figure 47 results in pavements with larger low temperature modulus of stiffness values. Furthermore, for pavements containing asphalt cements of the same penetration at 77°F, low temperature transverse pavement cracking is greater (and the low temperature moduli of stiffness are higher), when pavements contain low viscosity (low PI) rather than high viscosity (high PI) asphalt cements, Figure 35.

Consequently, the theoretical chart of Figure 47 supports Rader's (23, 24, 25) two conclusions that a low modulus of elasticity (stiffness) for a pavement at low temperature will reduce pavement cracking, and that the use of a softer asphalt cement will result in a lower modulus of elasticity for a pavement. This is also confirmed by Figure 37. Figures 35 and 47 also imply support for the conclusions of Hills and Brien (16) summarized in Figure 40, that the use of softer asphalt cements will lower the temperature at which low temperature thermal stresses cause pavement cracking, and that for pavements containing asphalt cements of the same penetration at 77°F, those containing asphalt cements with higher PI values (less temperature susceptible) can be subjected to lower temperatures without cracking than when they contain asphalt cements with lower PI values (more temperature susceptible). In agreement with Hills' and Brien's second conclusion, Figure 35 shows that after eight years of service, Ontario pavements containing 85/100 penetration asphalt with the lowest PI (approaching -1.5), developed from twenty to fifty times as many transverse cracks per mile as the pavements made with 85/100 penetration asphalt with the highest PI (approaching 0.0).

The temperatures indicated in Figure 40, at which low temperature thermal cracking was reported for paving mixtures made with the various asphalt cements investigated by Hills and Brien (16) in the laboratory, appear to be somewhat lower than the temperatures to which the pavements in Figures 5 to 25 had been subjected. This might be interpreted as indicating that the added stresses imposed by traffic at sub-zero temperatures may combine with the purely low temperature thermal stresses to cause pavement cracking at higher temperatures than those forecast on the basis of thermal stress alone.

17. Transverse Pavement Cracking and Grading of Asphalt Cements by Viscosity at 140°F Versus Grading by Penetration at 77°F

The problem of low temperature transverse pavement cracking in colder climates is so serious that it should exert a major influence on settling the current controversy over the proposed grading of asphalt cements by viscosity at 140°F versus their continued grading by penetration at 77°F.

Figure 30 illustrates grading by viscosity at 140° F versus grading by penetration at 77° for asphalt cements currently used in Canada. This chart also applies to many asphalt cements being used in the United States. Figure 31 shows the wide range in viscosity at 140°F, 500 to 2,000 poises, that is associated with the widely used 85/100 penetration grade. Asphalt concrete pavement construction operations are performed at high temperature, and this wide range of viscosity at 140°F and at higher temperatures, can lead to delayed rolling in hot weather, and other construction difficulties. To avoid these, it has been proposed that asphalt cements should be graded by viscosity at 140°F, and that the penetration test should be discarded. As illustrated by Figure 32, just one of the proposed viscosity grades at 140°F, AC 12, would include all present asphalt grades normally being employed in North America for pavement construction, 40/50, 60/70, 85/100, and 150/200 penetration. Grading by viscosity at 140°F implies therefore, that the long term service performance of pavements made with asphalt cements with this very wide range of penetration at 77°F, from 40 to approximately 200 penetration, would be identical. It will be demonstrated that this implication is dangerously misleading, particularly with respect to low temperature pavement performance.

Figure 47 indicates that the range in modulus of stiffness for slow loading at -10°F associated with paving mixtures containing each penetration grade is approximately four times, for example, 275,000 to 1,000,000 psi for the 85/100 penetration grade, and 90,000 to 400,000 psi for the 150/200 penetration grade. Figure 35 shows that this four-fold range in modulus of stiffness for paving mixtures made with the 85/100 penetration grade, can result in from a 20-fold to 50-fold increase in the number of transverse pavement cracks per mile due to low temperature stresses, after eight years of service.

Figures 30 and 32 demonstrate for the proposed AC 12 grade, that its penetration at 77°F ranges from 40/50 penetration for a PI of -1.5 to 150/200 penetration for a PI of 0.0. Referring to Figure 47, the cross-hatched area labelled AC 12 indicates that a paving mixture containing 150/200 penetration asphalt with a PI of 0.0 has a minimum modulus of stiffness of about 110,000 psi for slow loading at -10°F (low temperature thermal stresses), while for the same conditions, a paving mixture containing 40/50 penetration asphalt with a PI of -1.5 has a maximum modulus of stiffness of 2,250,000 psi. Consequently, for the proposed AC 12 grade, the range in modulus of stiffness for slow loading at -10°F is about 20 times. Similarly, the range in modulus of stiffness for slow loading at -10°F is also about 20-fold for both the AC 6 and AC 3 grades. Therefore, with Figure 35 in mind, it is clear that in areas subject to freezing weather, very severe transverse cracking could be expected for a pavement containing an AC 12, AC 6, or AC 3 asphalt cement with a low penetration at 77°F and a PI of -1.5, while much less, and even no transverse cracking would be anticipated for a pavement containing an AC 12, AC 6, or AC 3 asphalt cement with a high penetration at 77°F and a PI of 0. Consequently, in regions exposed to freezing conditions, Figures 30, 35, and 47, demonstrate very clearly that grading asphalt cements by viscosity at 140°F would result in very much more drastic variability in low temperature pavement performance with respect to transverse cracking, because of the 20-fold range in low temperature modulus of stiffness values associated with paving mixtures made with each viscosity grade, than would grading by penetration at 77°F with only a four-fold range in low temperature modulus of stiffness for each grade.

Some highway authorities are considering grading asphalt cements by viscosity at 140°F, but are proposing to also include with each viscosity grade a much wider range of penetration at 77°F than is permitted by current specifications that are based on penetration at 77°F. For example, to replace the current widely used 85/100 penetration grade, a much wider range of 60 to 120 penetration at 77°F has been proposed for use along with viscosity limits of 2,000 ± 400 poises at 140°F that in effect would stipulate a minimum PI of -1.2 in Figure 30. It has already been pointed out that for paving mixtures containing 85/100 penetration asphalt ranging in PI from 0.0 to -1.5, Figure 47 indicates a maximum range of modulus of stiffness from 275,000 to 1,000,000 psi, a four-fold range in modulus of stiffness, which Figure 35 indicates can result from a 20-fold to 50-fold range in the number of transverse cracks per mile of pavement. For paving mixtures containing asphalt cements with proposed limits ranging from 120 penetrations with a PI of 0 or higher to 60 penetration with a PI of -1.2, Figure 47 indicates that the corresponding range in modulus of stiffness is from 200,000 to 1,200,000 psi, a range in modulus of stiffness of six times. Quite obviously, paving mixtures containing asphalt cements satisfying the proposed specification based on viscosity at 140°F and penetration limits of 60 to 120, with their six-fold range in modulus of stiffness, will demonstrate much more variability in the range of transverse cracking at low temperatures, than would occur by retaining the standard 85/100 penetration grade with its associated four-fold range in modulus of stiffness.

Figure 48 is similar to Figure 47, but it pertains to a still colder climate, where as indicated by the abscissa, pavements containing the same grades of asphalt cements are subjected to low temperature stresses due to slow chilling to -25°F. Figure 49 is similar to Figure 47 but indicates the influence of a less severe climate on pavement moduli of elasticity. The ordinate axis in Figure 49 provides modulus of stiffness values for pavements containing the same grades of asphalt cements when subjected to fast loading at 140°F, while the abscissa gives corresponding moduli of stiffness values developed by the same pavements when slowly chilled to +10°F. In general, for the same paving mixtures, the graph of Figure 47 has been shifted to the right in Figure 48 to higher modulus of stiffness values for the abscissa, and to the left and downward in Figure 49 to lower modulus of stiffness values on both the abscissa and ordinate axis.

The principal reason for proposing the grading of asphalt cements by viscosity at 140°F, is to eliminate high temperature pavement construction problems that result from viscosity differences due to crude oil source when asphalts are graded by penetration at 77°F, Figure 31. However, as clearly indicated by the hatched area labelled AC 12 in Figures 47, 48, and 49, this would have a drastically detrimental effect on the variability of pavement cracking due to low temperature thermal stresses, since the associated range of modulus of stiffness is about 20-fold, whereas this range is only about four-fold for either 85/100 or 150/200 penetration asphalt cements.

The construction period is only from two to three hours, while the service life of a well designed and constructed asphalt pavement is from 20 to 25 years. Consequently, from the point of view of long term pavement performance, it would appear to be much more important to establish whether or not there is a method for grading asphalt cements, that for each grade would eliminate the viscosity differences due to crude oil source, that are responsible for the higher modulus of stiffness values and associated greater pavement cracking for pavements made with asphalt cements with a PI of -1.5 than with a PI of 0.0, Figures 47, 48, and 49. Figure 50 demonstrates that there is a method for grading asphalt cements that will achieve this objective. It requires grading asphalt cements by penetration at 32°F, 200 g, 60 sec. For paving mixtures containing each grade based upon penetration at 32°F, with the exception of the hardest grade, Figure 50 shows that their boundaries in terms of moduli of stiffness for slow loading at -10°F are vertical lines from a PI of 0.0 to a PI of -1.5. As may be determined from Figure 51, the grades based upon penetration at 32°F in Figure 50, are the same as those based upon penetration at 77°F and a PI of 0 in Figure 47. Figure 50 shows that the range in modulus of stiffness for slow loading at -10°F for paving mixtures containing each grade of asphalt cement is only about 1.5-fold, for example when the range in penetration at 32°F is from 23.4 to 26.8, the corresponding range in modulus of stiffness at -10F° is from 280,000 psi to 400,000 psi, a range of 1.4-fold. Consequently, Figure 50 demonstrates that grading asphalt cements by penetration at 32°F would provide pavements with the same moduli of stiffness under slow loading at -10°F, and therefore presumably with the same performance with respect to transverse pavement cracking, regardless of the temperature susceptibility characteristics (PI values) of the asphalt cements.

Figure 52 shows that when grading asphalt cements by penetration at 32°F, for each grade, under conditions of slow loading at +10°F, the moduli of stiffness of pavements containing asphalt cements with a PI of -1.5 are **less** than when they contain asphalt cements with a PI of 0.0. This implies that by grading asphalt cements by penetration at 32°F, for slow loading at +10°F and above, (actually for all temperatures above -10°F), there would be **less** transverse cracking of pavements containing asphalt cements with a PI of -1.5 than with a PI of 0.0 This would be the complete opposite to Figures 47, 48, and 49, where asphalts are graded by penetration at 77°F.

On the other hand, as indicated diagrammatically by Figure 53, if asphalt cements were graded by penetration at 32°F, for each grade there would be a very much wider variation in viscosity at 140°F than occurs when asphalts are graded by penetration at 77°F, Figure 31. Consequently, while grading asphalt cements by penetration at 32°F would be expected to eliminate differences in transverse pavement cracking due to differences in temperature susceptibility, that is to differences in penetration index, it would increase currently experienced high temperature construction difficulties.

To summarize therefore, insofar as low temperature pavement cracking is influenced by modulus of stiffness for slow loading at -10°F, Figures 47, 50, and 53, indicates that the four methods that have been considered here for grading asphalt cements, compare as follows.

Method of Grading Asphalt Cements	**Range of Modulus of Stiffness of Pavement per Asphalt Grade for Slow Loading at -10°F**
Grading by penetration at 32°F, 200g, 60 sec.	1.5-fold
Grading by penetration at 77°F, 100g, 5 sec.	4-fold
Grading by viscosity at 140°F but including a wide range of penetration at 77°F	6-fold
Grading by viscosity at 140°F and eliminating all reference to penetration at 77°F	20-fold

The following comments can be made on this comparison:

1. If an engineer were concerned only with pavement cracking at low temperature due primarily to thermal stresses, this comparison indicates that grading by penetration at 32°F is by far the best method for grading asphalt cements, because of the very narrow 1.5-fold range in modulus of stiffness for each grade. On the other hand, with regard to minimizing high temperature construction problems, Figure 53 demonstrates that grading asphalt cements by penetration at 32°F would be the worst method because it would provide the widest range of permissible viscosity at 140°F.
2. Grading by viscosity at 140°F is obviously by far the worst method for grading asphalt cements with regard to low temperature pavement cracking. Its 20-fold range in pavement modulus at -10°F for each grade, would lead to disastrously wide variability in pavement cracking at low temperatures, with pavements containing low penetration asphalts at 77°F, Figures 30 and 32, showing very drastic transverse cracking, while those containing high penetration asphalts would develop very much fewer and even no transverse cracks. However, Figure 53 indicates that with respect to reducing high temperature pavement construction problems, grading by viscosity at 140°F is the best of the four methods, because it provides the narrowest range of viscosity at 140°F for each grade.

Incidentally, the small circle in Figure 53 at a temperature of 275°F, indicates that if asphalt cements were graded by viscosity at 275°, as is sometimes proposed, the disadvantages of grading by viscosity at 140°F with regard to low temperature pavement cracking, would be multiplied.

3. Grading by viscosity at 140°F, but including a wider range of penetration at 77°F for each grade than normal, is decidedly inferior to grading by penetration at 32°F, or by penetration at 77°F, with respect to low temperature pavement cracking, because its six-fold range in modulus of stiffness for pavements under slow loading at -10°F, is very much more than the 1.5-fold range associated with grading by penetration at 32°F, and is substantially more than the 4-fold range that results from grading by penetration at 77°F. With regard to lessening high temperature construction problems, it is equivalent to grading by viscosity at 140°F.

4. While grading asphalt cements by penetration at 32°F is obviously the best method for grading asphalt cements with respect to low temperature pavement cracking (1.5-fold range in modulus of stiffness for each grade, Figure 50), it is the worst of the four methods with respect to minimizing high temperature construction problems, because as indicated by Figure 53, it would provide the widest range of viscosity at 140°F. On the other hand, while grading asphalt cements by viscosity at 140°F is the best of the four methods with regard to reducing construction problems at high temperatures, Figure 53, it is by far the worst method with respect to the wide variability of low temperature pavement cracking associated with each grade, Figures 47 and 53, (a 20-fold range in modulus of stiffness for each grade, Figure 47).

   Therefore, as frequently happens with asphalt materials, when the need for good paving mixture performance **both** at low temperatures in service, and at high temperatures for construction, is clearly recognized, a compromise between these two extreme methods for grading asphalt cements (by penetration at 32°F, or by viscosity at 140°F), would seem to be required. As indicated by the above table and by Figure 53, the best compromise would appear to be to continue grading asphalt cements in terms of their consistency at 77°F as measured either by the present penetration test or by a viscosity test. This would provide a workable solution intermediate between the other two methods, Figure 53, both for transverse pavement cracking and other low temperature pavement performance, and for construction problems at high temperature. As previously pointed out elsewhere (4), the temperature of 77°F is approximately at the centre of the significant range of pavement service temperature in Canada and the United States. If this temperature is exceeded by from 60 to 90°F, the pavement is approximately at its highest service temperature. If it is decreased by from 60 to 90°F, the pavement temperature approximates its lowest service temperature in most areas.

5. To summarize, for Canada and for the parts of United States where transverse pavement cracking is occurring due to low temperature conditions, Figures 30, 35, 47, 50 and 53 indicate that there is no more justification for grading asphalt cements by viscosity at 140°F to facilitate high temperature construction operations, but completely disregarding the disastrous effect this would have on low temperature pavement performance, than there is to grade asphalt cements by penetration at 32°F to eliminate or greatly lessen low temperature transverse pavement cracking, but overlooking the detrimental effect

this would have on high temperature construction operations. Figure 53 demonstrates very clearly that grading asphalt cements by either penetration or viscosity at 77°F provides a reasonable compromise between these other two extreme grading methods.

With respect to pavement cracking at low temperatures, if restrictive specifications for asphalt cements are to be considered, it is preferable that the restrictive specification should be based on grading paving asphalts by penetration at 77°F with a viscosity restriction, rather than grading them by viscosity at 140°F with a penetration at 77°F restriction. For example, 85/100 penetration asphalt with Line C in Figure 30 as a minimum viscosity requirement (PI = 0) is seen from Figure 47 to result in a permissible range in modulus of stiffness of only about 2.5-fold, from 275,000 psi to 700,000 psi, for slow loading at -10°F. On the other hand, it can be observed from Figures 30 and 47 that grading paving asphalts by viscosity at 140°F, for example, 2,000 ± 400 poises with a specified range of penetration at 77°F of 60 to 120, results in a permissible range of modulus of stiffness of about six-fold, from 200,000 psi to 1,200,000 psi (PI = 0 to PI = -1.2), for the same low temperature conditions. Since the wider the range of modulus of stiffness the more variable is the degree of transverse pavement cracking, these data imply that a restrictive specification based on grading by penetration at 77°F and a minimum viscosity requirement at 140°F or at 275°F, with its 2.5-fold range of modulus of stiffness, is greatly superior to a restrictive asphalt cement specification based on viscosity at 140°F and wider than normal limits for penetration at 77°F, with its six-fold range of modulus of stiffness.

In conclusion, it should be emphasized that nearly every asphalt cement that satisfies current ASTM specifications will result in pavements that perform well, **provided the proper grade is selected,** and good design and construction practice is followed. For instance, when selecting the grade of asphalt cement to be used in a region subject to freezing conditions, either to eliminate or to achieve a large reduction in transverse pavement cracking, the selection should be governed by the highest modulus of stiffness for the pavement that experience has shown will enable this result to be achieved. This will provide higher pavement stability for warm weather traffic. If for example, pavements of a given design containing 85/100 penetration asphalt **with a PI of 0.0** are found to show little or no transverse cracking due to low temperature thermal stresses at -10°F, Figure 47 indicates that when asphalt cements **with a PI of -1.5** are being considered, the same pavements should contain 150/200 penetration asphalt as the hardest grade. For slow loading at -25°F, Figure 48 shows that pavements of a given design containing 85/100 penetration asphalt **with a PI of 0.0,** or 200/300 penetration asphalt **with a PI of -1.5,** have the same modulus of stiffness, and would therefore be expected to exhibit similar degrees of transverse cracking. Similarly, for the milder climate illustrated by Figure 49, for slow loading at +10°F, pavements of a specified design containing 85/100 penetration asphalt cement **with a PI of 0.0** or 100/120 penetration asphalt **with a PI of -1.5,** have approximately the same modulus of stiffness, and would be expected therefore to show like transverse cracking. By designing paving mixtures for the maximum modulus of stiffness that will avoid transverse pavement cracking under low temperature conditions, the effect on the selection of asphalt cements is to associate a **high viscosity (high PI)** asphalt cement of a **given penetration** at 77°F, for example, 85/100 penetration with a PI of 0.0, **with a low viscosity (low PI)** asphalt cement of a **higher penetration** at 77°F, for example 150/200 penetration with a PI of -1.5.

As a first impression, this suggested method of selecting the penetration grade of asphalt cement for a paving mixture may be questioned, because of the range of penetration grades it would permit for any given paving project. Nevertheless, engineers need to realize that this is precisely what the suggested grading of asphalts by viscosity at 140°F (and the associated proposal to discard penetration at 77°F) would actually do, **but unfortunately by broadening the range of penetration at 77° in the wrong direction.** For example, as shown by Figure 30, for the proposed AC 12 grade, the associated range in penetration at 77°F is from 40/50 to 150/200, for the AC 6 grade it is from 70/85 to 200/300, and for the AC 3 grade it is from 120/150 to 300/400 penetration. The proposed grading by viscosity at 140°F, e.g. AC 12, associates a high viscosity (high PI) asphalt cement of higher penetration at 77°F, for example, 150/200 penetration and a PI if 0.0, with a low viscosity (low PI) asphalt cement of lower penetration at 77°F, for example, 40/50 penetration and a PI of -1.5, Figures 47, 48, and 49.

As a result, the range in pavement low temperature moduli of stiffness due to differences in asphalt temperature susceptibility associated with each viscosity grade, e.g. AC 12, is greatly widened (20-fold in Figure 47), and the corresponding variability in transverse pavement cracking is drastically increased instead of being reduced or eliminated.

As engineers, we should be sufficiently well informed to be able to satisfactorily employ all suitable paving materials that are locally available. This includes asphalt cements as well as aggregates. The more restrictive the specification for any material becomes, the higher its cost will eventually be. There appears to be a current tendency in many areas to assume that for any penetration grade of asphalt cement, only high viscosity (high PI) asphalt cements should be specified. This fails to recognize the thoroughly demonstrated excellent service performance of many pavements that have been made with **properly selected** grades of low viscosity asphalt cements. It also seems to be overlooked that low viscosity asphalt cements provide paving mixtures with less resistance to compaction by rolling; they provide a longer period of time during which compaction by rolling is effective, which is a very important advantage in colder climates; pavements compact faster to ultimate density under traffic, which retards the rate of hardening of the asphalt binder in service, and lengthens pavement service life; and they provide pavements with substantially greater load carrying capacity per inch of thickness during the spring break-up period.

Finally, provided the old pavement is first covered with a substantial layer of stable granular material, it is believed that the use of softer asphalt cements in asphalt concrete overlays, would effectively reduce the amount of reflective cracking in the overlay that is presently occurring.

SUMMARY AND CONCLUSIONS

1. With the exception of the warmer region of southern Ontario, the transverse pavement cracking problem in the settled part of Canada is most serious between the Rocky Mountains and the mouth of the St. Lawrence River, where the freezing index ranges from 1,000 to 4,000.
2. A freezing index range of from 1,000 to 3,000 also pertains to a large area of the northern United States.
3. The history of the use of gradually harder asphalt binders on rural highways in Canada since the 1930's, indicates that transverse pavement cracking did not become a problem until the 1950's when 150/200 penetration asphalt was first introduced into pavement construction in the Prairie Provinces, and 85/100 penetration into pavement construction in northern Ontario and Quebec.
4. Other evidence is cited relating transverse pavement cracking to the hardness of the asphalt cement employed.

5. Photographic evidence illustrating pavement performance in Ontario, Alberta, Saskatchewan, and Manitoba, demonstrates that transverse cracking is the most severe in northern Ontario where 85/100 penetration has been employed, but is greatly reduced or completely disappears when 300/400 penetration asphalt cement or SC 3,000 (SC 5) are used.

6. It is recognized that the subgrade and granular base may be responsible for some transverse cracking. Nevertheless, little or no transverse cracking was observed when the softest grades of asphalt cement were employed. This leads to a tentative conclusion that low temperature transverse pavement cracking is ordinarily due more to the characteristics of the paving mixture than to the foundation.

7. Analysis of pavement samples taken from the Trans-Canada Highway immediately north of the Great Lakes showed that transverse pavement cracking was practically eliminated when the recovered asphalt cement was softer than 60 penetration at 77°F, and softer than 20 penetration at 32°F. In colder areas than this particular region, there is evidence that the recovered asphalt must be still softer.

8. For a Test Road in Saskatchewan, 2-inch test pavements were laid with 150/200 penetration asphalt cements ranging in viscosity at 140°F from intermediate to high (intermediate to high PI). A transverse crack survey **at the end of two years** indicated that the pavements made with 150/200 penetration asphalt cement of intermediate viscosity (intermediate PI) had twice as many cracks per mile as pavement sections made with 150/200 penetration asphalts with high viscosity (high PI).

   Three Test Roads in southwestern Ontario were each constructed with 3-inch pavements containing 85/100 penetration asphalts of high viscosity (high PI), intermediate viscosity (intermediate PI), and low viscosity (low PI). **After eight years, a** transverse crack survey indicated that the pavements containing the low viscosity (PI = -1.64) 85/100 penetration asphalt, had from 20 to 50 times as many transverse cracks per mile as the pavements made with 85/100 penetration high viscosity (PI approaching 0.0) asphalt cements.

   On a nine-mile Test Road in the same general area in southwestern Ontario, two-inch pavements were laid with low viscosity (PI = -1.64) 85/100 and 150/200 penetration asphalt cements from the same crude oil source. The low viscosity 85/100 penetration asphalt was the same as that supplied for the other three Test Roads. A transverse crack survey made **after six years** showed many more transverse cracks per mile in the pavement section of this Test Road made with the low viscosity (low PI) 85/100 penetration asphalt cement, than developed after eight years in any paved section of the other three Test Roads. Nevertheless, the pavement portion of this Test Road made with 150/200 penetration low viscosity (low PI) asphalt cement, showed no transverse cracks of any kind. Its performance was superior to that of even the highest viscosity (high PI) 85/100 penetration asphalt in the other three Test Roads. This provides further evidence of the effectiveness of the use of softer asphalt cements for reducing low temperature transverse pavement cracking.

9. Experience shows that little reduction in transverse cracking occurs by changing to the adjacent softer grade. It is necessary to jump over one or two grades to a softer grade of asphalt cement.

10. Figure 30 demonstrates that the large differences in viscosity at 140°F that are associated with the harder lower penetration asphalts, become much smaller for asphalt cements of 300/400 penetration and softer.

11. Because SC 6 asphalt includes all grades of asphalt cement from 150/200 to 600 penetration depending on crude oil source, this grade brackets asphalt cements that can show serious transverse cracking with those that do not. Consequently, the SC 6 grade should be discarded from all specifications in which it appears, and it should be replaced by a specification for 300/400 penetration asphalt cement.

12. Every engineer must use his best engineering judgment when deciding the grade of asphalt cement that will provide pavements with minimum transverse cracking in cold weather consistent with the need for adequate stability for traffic in hot weather.

13. To retard the rate of hardening of the asphalt binder in service, special specifications for SC 3,000 (SC 5) and SC 800 (SC 4) may have to be developed stipulating that little or no solvent is to be recovered at 680°F.

14. It is shown that the present investigation of transverse pavement cracking in Canada, is in a sense an extension of a review by The Asphalt Institute in the 1930's of the pavement cracking problem in the central Mid-West, and central Atlantic Coast regions of the United States, which indicated a close relationship between pavement cracking and hardness of the asphalt binder.

15. The adoption of softer grades of asphalt cements to reduce transverse pavement cracking could lead to two practical problems:

    (a) delayed rolling behind the spreader because of softness of the paving mixtures at high temperatures

    (b) rapid densification of a new pavement by traffic to 100 percent of laboratory compacted density, which could lead to flushing or bleeding a few months after construction unless the paving mixture is properly designed.

    It is shown that the use of pneumatic-tire rollers equipped for rapid adjustment of tire inflation pressure provides a solution to the first problem, and designing paving mixtures to have a minimum air voids value of 3 percent provides a simple and practical solution to the second.

16. Because soft asphalt cements should be about the same price as harder asphalt cements, the use of softer asphalt cements to solve the problem of transverse pavement cracking should not increase the initial cost of a pavement. Furthermore, there would be a substantial annual savings in the maintenance cost of filling from 100 to 300 or more cracks per mile per year.

17. It is shown that based on the work of Rader, Pfeiffer and Van Doormaal, Van der Poel, Heukelom and Klomp, and Hills and Brien, there are sound theoretical reasons for going to softer asphalt cements to reduce or eliminate transverse pavement cracking.

18. The single most significant criterion of the amount of cold weather transverse pavement cracking to be expected in any given area, appears to be the modulus of stiffness of the pavement at the minimum temperature to which it will be exposed in service. Figures 47, 48, and 49 indicate that for any given paving mixture design, its modulus of stiffness at any specified low temperature depends upon the hardness of the asphalt cement it contains.

19. However, Figure 37 demonstrates that for any given modulus of stiffness of a paving mixture, the associated amount of low temperature transverse pavement cracking that develops, varies from paving project to paving project. This indicates that cold weather transverse pavement cracking depends upon other factors than the characteris-

tics of the asphalt cement it contains. Nevertheless, evidence accumulated to date demonstrates very clearly that low temperature transverse pavement cracking can be drastically reduced and even eliminated by using a softer grade of asphalt cement.

20. As a general conclusion, both the field and the theoretical evidence presented in this paper indicates that wherever cold weather transverse pavement cracking is occurring in Canada, it can be greatly lessened and even eliminated by changing to a softer grade of asphalt cement. This could require a change for example to 150/200 penetration asphalt cement in milder winter climates, to 300/400 penetration paving asphalt in colder areas, and to SC 3,000 (SC 5) or even to SC 800 (SC 4) in the coldest regions. Elsewhere, the choice of a softer grade of asphalt cement should be guided by local conditions of climate, temperature, and traffic.

21. Finally, consideration for low temperature transverse pavement cracking has much to contribute toward the solution of the current controversy over the proposed grading of asphalt cements by viscosity at 140°F versus their continued grading by penetration at 77°F, Figure 30. When asphalt cements are graded by penetration at 77°F, the range in low temperature modulus of stiffness values for paving mixtures containing any one penetration grade of asphalt cement is only four-fold, Figure 47, and Figures 35 and 47 indicate that this is associated with a corresponding range of from 20-fold to 50-fold in the amount of transverse cracking that can occur in eight years. The cross hatched band in Figure 47 labelled AC 12, indicates that grading asphalt cements by viscosity at 140°F would provide paving mixtures for which the range in modulus of stiffness values for slow loading at -10°F (low temperature thermal stresses) would be 20-fold for each viscosity grade of asphalt cement. Consequently, the amount of transverse pavement cracking associated with viscosity at 140°F grade of asphalt cement would be expected to be several times the 20-fold to 50-fold number of cracks associated with each penetration at 77°F grade. Paving mixtures containing low penetration (low PI) asphalts associated with each viscosity grade, Figure 30, would show extremely serious low temperature transverse cracking, while identical paving mixtures containing high penetration (high PI) asphalts belonging to the same viscosity at 140°F grade, would show very much less and even no transverse cracking. Consequently, the causes of low temperature transverse pavement cracking and their proposed solution, that have been outlined in this paper, firmly oppose grading asphalt cements by viscosity at 140°F, and actively support their continued grading by consistency at 77°F as measured either by the penetration test, or by a viscosity test.

ACKNOWLEDGMENTS

Grateful acknowlegment is made to Mr. J. A. A. Lefebvre of our Research Department for his careful analysis of the pavement samples, and for other data, to my associate Mr. C. L. Perkins for his skillful drafting of the diagrams for this paper, and to Messrs. Alex Rutka, Frank Norman and D. Donovan of the Ontario Department of Highways, to Mr. F. D. Young of the Manitoba Department of Public Works, to Mr. J. M. Dacyszyn of the Alberta Department of Highways, and to Messrs. W. E. Winnitoy, M. F. Clark, R. W. Culley and J. W. Scott of the Saskatchewan Department of Highways and Transportation, for their many courtesies, and particularly for their assistance with regard to pavement samples, concerning grades of asphalt cement employed, dates of construction, and other useful information pertaining to the various pavement projects examined.

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TABLE 1

TYPICAL INSPECTION DATA ON PAVING MIXTURES FOR FIGURES 5 TO 25

TEST ITEM	FIGURES														
	5	6	7	8	9	10	11	13	14	17	21	22	23	24	25
Year Pavement Constructed	1961	1960	1960	1962	1963	1961	1961	1961	1963	1959	1960	1963	1952	1965	1965
Inspection Data During Construction						x	x	x	x	x	x	x	x	x	x
Inspection Data from 1967 Pavement Sample	x	x	x	x	x										
Asphalt Cement Grade	85/100	150/200	85/100	150/200	150/200	85/100	150/200	85/100	150/200	150/200	150/200	150/200	SC 6 300/400	SC 6 300/400	SC 5 SC 3000
Asphalt Content Per Cent	4.96	5.67	5.75	4.42	5.21	6.3	6.3	5.12	5.5	6.61	5.0	5.2		5.1	4.8
Sieve Analysis of Aggregate															
Pass ¾ inch	100	100	100	100	100	100	100	100	100	100	100	100		100	100
" ½ "	93.9	94.3	95.2	97.8	95.6	97	97	89.5	83	95	94	93		90	93
" ⅜ "	82.8	82.5	81.7	81.5	78.0	82	82	85.2	72	87	83	82		81	84
" No. 4 sieve	55.4	59.4	63.0	58.9	55.9	59	59	54.1	52	66	64	62		65	65
" " 8 "	42.3	44.3	49.8	46.7	44.7	50	50	43.7	37	51	52	57		54	50
" " 16 "	33.4	31.8	38.9	36.0	34.5	39	39	34.8	28	32	43	33	NOT AVAILABLE	44	38
" " 30 "	26.6	21.6	29.8	25.4	25.2	27	27	23.6	23	19	33	22		31	28
" " 50 "	19.9	12.1	17.9	14.6	14.4	14	14	10.6	18	12	24	14		21	19
" " 100 "	9.3	6.3	6.4	7.3	6.4	8	8	5.9	11	8	14	9		12	12
" " 200 "	4.6	3.8	3.9	4.1	3.9	6	6	4.1	4.0	4.2	5.2	7		4.0	4.5
Marshall Test Data															
No. of blows compaction	75	75	75	75	75	75	75	75	50	50		50		50	50
Marshall Stability at 140°F	3675*	2550*	2400*	2625*	2650*	1800	1400	1800	1215	1214		1400		550	900
Marshall Flow Index	10.5	10.0	10.0	10.0	9.0	14.5	14.5	15	11.9	6.0		14		8.0	10.0
% Air Voids	2.3	2.2	1.3	3.7	2.3	0.9	0.9	2.4	4.7	2.6		4.0		4.5	5.0
% Voids in Mineral Aggregate (VMA)	13.5	14.0	14.7	13.6	13.9	14.1	14.1	14.7	15.6	15.4		16.5		17.0	16.0

*Recompacted pavement samples

TABLE 2

TYPICAL INSPECTION DATA ON ORIGINAL ASPHALT CEMENTS FOR FIGURES 5 TO 25

TEST ITEM	FIGURES														
	5	6	7	8	9	10	11	13	14	17	21	22	23	24	25
Grade of Asphalt Cement	85/100	150/200	85/100	150/200	150/200	85/100	150/200	85/100	150/200	150/200	150/200	150/200	SC 6 300/400	SC 6 300/400	SC 5 SC 3000
Flash Point °F COC			650	650	650	630	680	630		520	520	515		460	455
Penetration at 77°F	99	174	96	171	180	93	172	93		204	166	162			
Viscosity															
at 275°F centistokes	226	204	211	233	227	192	119	192		190					
at 210°F SSF														352	
at 180°F SSF															418
Ductility 5 cm/Min cms															
at 77°F			126	150+	150+	143		143	NOT AVAILABLE	120+	100+	100+	NOT AVAILABLE		
at 60°F							150+								
Loss on Heating 325°F 5 hr. 50 g.															
% loss by weight			0.0022	Nil	Nil	0.0144	0.004	0.0144		0.1					
Pen at 77°F, % of original			80.8	81.5	81.5	88.5	91.2	88.1		86.0	78.0	88.0			
Distillation:															
Total distillate to 680°F															
Float test on residue at 122°F														276	190
Solubility in carbon tetrachloride			99.5	99.9	99.9	99.7	99.5	99.7		99.9					

TABLE 3

INSPECTION DATA ON NORTHERN ONTARIO PAVEMENT SAMPLES TAKEN IN 1967

TEST ITEM Sample Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Year Pavement Constructed	1957	1957	1960	1961	1957	1957	1961	1961	1962	1961	1961	1961	1963	1963	1960	1960	1963	1962	1960	1960
Asphalt Cement, Grade (Original)	150/200	150/200	150/200	85/100	150/200	150/200	150/200	85/100	85/100	85/100	85/100	85/100	85/100	150/200	150/200	150/200	150/200	150/200	85/100	85/100
Asphalt Content, Per Cent (Recovered)	5.39	6.01	5.67	4.96	4.78	5.83	5.21	5.69	5.50	5.74	5.22	5.30	5.68	5.44	5.02	5.28	4.42	5.21	5.95	5.75
Sieve Analysis Recovered Aggregate																				
Pass ¾ inch	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
" ½ "	89.8	96.0	94.3	93.9	90.7	95.8	98.1	96.1	93.5	91.6	91.2	95.1	95.8	91.6	91.5	90.8	95.6	97.8	96.6	95.2
" ⅜ "	78.4	86.4	82.5	82.8	70.2	83.4	84.4	83.5	79.8	77.3	73.8	76.6	78.6	74.2	76.6	80.8	78.0	81.5	83.5	81.7
" No. 4 Sieve	56.7	64.0	59.4	55.4	54.8	61.2	66.5	61.7	55.6	52.6	49.1	54.5	55.3	55.7	60.1	60.7	55.9	58.9	65.0	63.0
" " 8 "	44.9	46.0	44.3	42.3	46.0	48.4	54.9	51.8	47.7	44.8	40.7	45.8	45.7	45.5	48.5	46.7	44.7	46.7	52.3	49.8
" " 16 "	32.6	31.5	31.8	33.4	35.2	36.4	44.7	41.1	39.8	38.1	33.8	38.2	37.4	33.0	37.9	32.9	34.5	36.0	42.5	38.9
" " 30 "	23.0	21.8	21.6	26.6	21.4	26.3	34.2	28.7	28.2	30.2	26.4	29.8	29.0	21.8	28.3	21.7	25.2	25.4	33.7	29.8
" " 50 "	14.4	13.8	12.1	19.9	10.6	16.3	18.4	14.0	12.4	17.9	16.3	17.3	17.9	10.2	19.2	12.2	14.4	14.6	19.9	17.9
" " 100 "	8.3	8.2	6.3	9.3	6.3	9.4	7.1	6.1	5.2	8.8	8.4	8.7	8.9	4.7	7.6	7.4	6.4	7.3	7.1	6.4
" " 200 "	5.9	5.8	3.8	4.6	4.5	5.8	3.8	3.1	2.8	4.5	4.3	4.5	4.3	2.7	5.4	5.2	3.9	4.1	4.1	3.9
Specific Gravity Recovered Aggregate																				
ASTM bulk	2.724	2.722	2.641	2.661	2.672	2.719	2.674	2.658	2.657	2.647	2.652	2.651	2.645	2.636	2.635	2.644	2.752	2.693	2.722	2.723
ASTM apparent	2.799	2.797	2.701	2.712	2.804	2.765	2.708	2.688	2.681	2.694	2.693	2.685	2.682	2.683	2.677	2.684	2.807	2.754	2.783	2.779
Virtual	2.786	2.787	2.691	2.684	2.717	2.759	2.697	2.680	2.681	2.688	2.675	2.685	2.679	2.665	2.665	2.668	2.785	2.724	2.737	2.742
Water absorption, Wt. %	0.95	0.93	0.85	0.71	1.77	0.61	0.49	0.43	0.34	0.66	0.57	0.50	0.51	0.66	0.60	0.57	0.72	0.82	0.80	0.70
Asphalt absorption, Wt. %	0.83	0.87	0.70	0.32	0.63	0.54	0.32	0.31	0.34	0.58	0.32	0.50	0.47	0.42	0.43	0.34	0.44	0.42	0.21	0.26
Marshall Test Data on Pavement Sample																				
No. of blows for recompaction*																				
Marshall Stability (recompacted)	2750	2150	2550	3675	2600	2450	2100	2625	2500	2800	2400	3350	3250	2480	2450	2500	2650	2625	2075	2400
Flow index (recompacted)	15.0	12.5	10.0	10.5	9.5	17.0	8.5	8.5	10.0	10.0	10.5	10.0	10.0	8.5	8.5	9.5	9.0	10.0	10.0	10.0
% air voids (as received)	2.0	1.6	4.8	5.2	6.7	2.3	5.7	6.2	6.1	3.9	0.9	3.4	1.6	6.7	5.2	5.1	7.3	3.5	2.3	1.8
% air voids (recompacted)	0.8	0.6	2.2	2.3	2.8	0.7	4.4	3.9	4.7	1.5	0.2	2.2	1.4	3.3	2.9	2.0	3.7	2.3	1.7	1.3
% lab compacted density as received	98.8	99.0	97.3	97.0	96.0	98.3	98.7	97.5	98.5	97.6	99.1	98.8	99.7	96.4	97.7	96.9	96.3	98.8	99.3	99.4
% voids in mineral aggregate (recompacted)	12.3	13.5	14.0	13.5	12.9	13.8	16.0	16.1	16.6	10.0	13.6	13.8	13.9	15.1	13.9	13.8	13.6	13.9	15.6	14.7

*60 blows mechanical compactor

TABLE 4

INSPECTION DATA ON ORIGINAL AND ON RECOVERED ASPHALT CEMENT FROM NORTHERN ONTARIO PAVEMENT SAMPLES TAKEN IN 1967

SAMPLE NO.	TRANSVERSE CRACKS PER 1000 FEET				PENETRATION TEST				PEN RATIO	VISCOSITY AT 275°F		VISC. AT 140°F	DUCTILITY CM	
	TYPES				ORIGINAL at 77°F 100 g 5 sec Average	RECOVERED AT			$\frac{39.2}{77} \times 100$ Recovered	Original Centistokes Average	Recovered Centistokes	Recovered poises	Recovered	
	1	2	3	4		77°F 100 g 5 sec	39.2°F 200 g 60 sec	32°F 200 g 60 sec					at 77°F 5 cm/Min	at 39.2°F 1 cm/Min
1	6	200	116	88	182	58	23	18.0	39.6	168	355	2282	150+	9.2
2	4	13	32	8	182	78.5	29	20.0	37.2	168	265	1157	150+	8.7
3	3	—	—	—	174	71	28.5	23.0	40.1	204	380.5	1813	150+	10.4
4	97	—	110	19	99	32	13.8	12.0	42.9	226	513.5	6954	150+	0.2
5	100	60	32	42	160	32.5	14.2	11.7	43.9	144	433.5	5647	88.0	0.2
6	80	192	90	141	161	47.5	20	12.5	42.1	139	348	2838	112.5	4.6
7	58	14	17	9	150	51.5	21.5	15.0	41.8	216	405	3065	150+	6.1
8	103	43	20	23	93	28	12.5	9.5	44.6	201	437	5825	150+	0.5
9	90	50	10	35	97	32	13.2	11.0	41.4	251	449.5	6897	79	0.2
10	108	40	37	15	88	41.4	14.0	10.8	33.8	202	377	3672	150+	0.2
11	104	55	124	25	94	57.5	17.3	14.0	33.2	202	278.5	1322	150+	5.0
12	112	34	80	24	94	33.5	13.5	11.5	40.4	202	372	3862	150+	0.2
13	110	38	98	20	94	31	11.5	10.0	37.1	202	385.5	4650	150+	0.5
14	54	4	29	—	158	54.5	21.5	16.5	39.4	214	398.5	2690	150+	6.0
15	90	65	23	10	169	39	14	9.0	35.9	130	246.5	2037	150+	0.8
16	85	4	11	2	171	39	15	9.0	38.4	135	262	2075	150+	0.5
17	2	—	—	—	180	60	27	22.5	45.1	227	432.5	3912	150+	5.2
18	2	—	—	—	171	64.5	29.5	23.0	45.7	233	393	2601	150+	5.6
19	57	16	65	9	96	41	17	14.5	41.5	211	359.5	3011	150+	0.5
20	76	44	168	34	89	50	20	15.5	40.0	231	329.5	2614	131.5	4.1

TABLE 5

INSPECTION DATA ON SOUTHERN ONTARIO PAVEMENT SAMPLES TAKEN IN 1968

TEST ITEM	SAMPLE NUMBER			
	1	2	3	4
Year Pavement Constructed	1961	1961	1961	1961
Asphalt Cement, Grade (Original)	85/100 pen.	85/100 pen.	150/200 pen.	150/200 pen.
Asphalt Content, Per Cent (Recovered)	6.68	6.50	6.44	5.78
Sieve Analysis Recovered Aggregate				
Pass 3/4 inch	100.0	100.0	100.0	100.0
" 1/2 "	96.2	97.6	99.2	99.2
" 3/8 "	85.8	86.1	87.4	83.5
" No. 4 Sieve	66.2	66.1	68.4	62.7
" " 8 "	55.0	55.2	54.8	50.9
" " 16 "	44.7	44.8	42.3	41.3
" " 30 "	32.3	33.8	31.0	30.6
" " 50 "	17.3	17.1	17.0	17.2
" " 100 "	8.9	8.2	9.4	9.1
" " 200 "	6.2	5.6	6.5	6.2
Specific Gravity Recovered Aggregate				
ASTM bulk	2.646	2.646	2.646	2.646
ASTM apparent	2.762	2.762	2.762	2.762
Virtual	2.697	2.704	2.706	2.698
Water absorption, Wt. %	1.59	1.59	1.59	1.59
Asphalt absorption, Wt. %	0.73	0.83	0.84	0.73
Marshall Test Data on Pavement Sample				
No. of blows for recompaction*				
Marshall Stability (recompacted), lb.	2100	2440	1510	1435
Flow Index (recompacted) (Units of 0.01 inch)	15	14	12	12
% air voids (as received)	2.9	4.0	1.8	2.6
% air voids (recompacted)	0.9	1.3	0.7	1.3
% laboratory compacted density as received	98.0	97.3	98.9	98.6
% voids in mineral aggregate (recompacted)	15.0	14.8	14.4	13.6

* 60 blows mechanical compactor

TABLE 6

INSPECTION DATA ON ORIGINAL AND ON RECOVERED ASPHALT CEMENTS FROM SOUTHERN ONTARIO PAVEMENT SAMPLES TAKEN IN 1968

SAMPLE NO.	TRANSVERSE CRACKS PER 1000 FT.				PENETRATION TEST				PEN. RATIO	VISCOSITY AT 275°F		VISCOSITY AT 140°F	DUCTILITY CM	
	TYPES				ORIGINAL AT 77°F 100 gr.5 sec. AVERAGE	RECOVERED AT			$\frac{39.2}{77}$ x 100 Recovered	Original Centistokes Average	Recovered Centistokes	Recovered Poises	Recovered	
	1	2	3	4		77°F 100 gr.5 sec.	39.2°F 200 gr.60 sec.	32°F 200 gr.60 sec.					at 77°F 5 cm/min	at 39.2°F 1 cm/min
1	Not Available (See Figure 10)				90	42	14	11	33.3	192	307	2045	150+	3.5
2	80	40	41	4	90	46	15	11	32.6	192	304	2123	150+	3.8
3	Nil				176	140	29	22	20.7	134	180	505	148	13.4
4	Nil				176	125	26	20	20.8	134	195	516	96	13.1

TABLE 7

INSPECTION DATA ON MANITOBA PAVEMENT SAMPLES TAKEN IN 1967 AND 1968.

TEST ITEM	SAMPLE NUMBER									
	1	2	3	4	5	6	7	8	9	10
Year Pavement Constructed	1965	1952	1951	1960	1965	1963	1965	1965	1965	1964
Asphalt Cement, Grade (Original)	150/200	SC-6	SC-6	150/200	SC-6	150/200	SC-5	SC-5	SC-5	150/200
Asphalt Content, Per Cent (Recovered)	4.69	5.29	5.0	4.71	4.78	5.7	4.54	5.15	5.0	4.52
Sieve Analysis Recovered Aggregate										
Pass 3/4 inch	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
" 1/2 "	97.5	91.9	94.6	96.4	98.1	91.4	90.6	94.0	93.2	90.5
" 3/8 "	82.8	85.0	86.1	82.9	83.1	81.4	74.2	79.3	78.6	76.8
" No. 4 Sieve	64.5	70.6	68.9	62.4	63.3	61.4	53.5	60.2	57.3	57.1
" " 8 "	53.3	58.4	54.4	49.7	52.2	46.2	44.4	47.1	47.3	45.7
" " 16 "	42.0	44.0	43.1	40.5	43.5	32.3	35.4	36.7	38.7	36.2
" " 30 "	29.9	29.0	35.2	33.8	35.9	24.5	26.6	28.2	29.8	27.5
" " 50 "	13.6	18.5	23.1	23.7	22.8	17.8	14.0	16.4	16.9	15.7
" " 100 "	5.1	8.2	9.4	8.7	9.0	11.9	6.0	7.2	7.1	7.2
" " 200 "	3.5	6.5	6.4	4.5	6.4	9.1	5.2	5.7	6.1	5.8
Specific Gravity Recovered Aggregate										
ASTM bulk	2.635	2.637	2.649	2.659	2.569	2.573	2.583	2.541	2.580	2.558
ASTM apparent	2.759	2.754	2.759	2.743	2.753	2.741	2.747	2.740	2.751	2.728
Virtual	2.721	2.728	2.740	2.698	2.660	2.666	2.662	2.674	2.679	2.646
Water Absorption Wt. %	1.71	1.15	1.5	1.15	2.60	2.39	2.25	2.85	2.41	2.45
Asphalt Absorption, Wt. %	1.21	0.96	1.26	0.56	1.33	1.36	1.14	1.96	1.43	1.33
Marshall Test Dat on Pavement Sample										
No. of blows for recompaction *										
Marshall Stability 140°F (recompacted)	1400	1650	1770	1000	2175	2350	1650	2075	1875	2300
Flow Index (recompacted)	6.5	8.0	7.5	6.0	7.0	15.5	8.0	9.0	8.0	9.0
% air voids (as received)	9.1	5.5	5.7	4.6	9.7	7.4	6.6	10.6	4.8	7.4
% air voids (recompacted)	6.1	3.0	3.9	3.2	4.4	1.6	3.4	5.0	2.0	3.1
% lab compacted density as received	96.8	97.4	98.1	98.5	94.5	94.0	96.7	94.1	97.2	95.5
% voids in mineral aggregate (recompacted)	14.4	13.0	13.1	13.2	12.6	12.2	11.7	12.7	11.7	10.9

* 60 blows Marshall mechanical compactor

TABLE 8

INSPECTION DATA ON ORIGINAL AND ON RECOVERED ASPHALT CEMENT FROM MANITOBA PAVEMENT SAMPLES TAKEN IN 1967 AND 1968

SAMPLE NO.	TRANSVERSE CRACKS PER 1000 FT.				PENETRATION TEST				PEN. RATIO	VISCOSITY AT 275°F	VISCOSITY AT 140°F	DUCTILITY CM	
	TYPES				ORIGINAL	RECOVERED AT						Recovered	
	1	2	3	4	AT 77°F 100 gr.5 sec. AVERAGE	77°F 100 gr.5 sec.	39.2°F 200 gr.60 sec.	32°F 200 gr.60 sec.	$\frac{39.2}{77} \times 100$ Recovered	Recovered Centistokes	Recovered Poises	at 77°F 5 cm/min	at 39.2°F 1 cm/min
1	31	4	20	1	150/200	60	18.5	13	30.8	183	853	150+	4.8
2	2	0	0	0	SC-6	160	62	51	38.8	246	808	150+	50+
3	same as (2)				SC-6	133	56	43	42.1	270	966	150+	50+
4	76	14	14	0	166	81	21	16	25.9	177	658	115	5.9
5	0	0	0	0	SC-6	143	45	34	31.5	218	587	140	50+
6	102	10	11	2	162	61	22	18	36.1	398	2185	150+	8.6
7	0	0	0	0	SC-5	339	92	69	27.1	135	202	96	50+
8	same as (7)				SC-5	374	125	91.5	33.4	112	132	60	50+
9	0	0	0	0	SC-5	320	102	74	31.9	127	189	65.5	50+
10	54	14	16	4	150/200	78	23.5	19	30.1	164	622	104	5.0

TABLE 9

INSPECTION DATA ON PAVING MIXTURE EMPLOYED FOR SASKATCHEWAN TEST PAVEMENT SECTIONS

Asphalt Type	150/200 Penetration
Asphalt Content percent	5.37
Aggregate Sieve Analysis	
Pass ¾ inch	100
Pass ½ inch	92
Pass ⅜ inch	88
Pass No. 4 Sieve	58
Pass No. 8 Sieve	39
Pass No. 16 Sieve	24
Pass No. 30 Sieve	15
Pass No. 50 Sieve	11
Pass No. 100 Sieve	8
Pass No. 200 Sieve	6.3
Marshall Test Data	
Marshall Stability at 140°F, lb.	1170
Marshall Flow Index	7
Percent Air Voids	4.0
Percent Voids in Mineral Aggregate	14.5

TABLE 10

INSPECTION DATA ON ORIGINAL 85/100 PENETRATION ASPHALT CEMENTS USED FOR ONTARIO'S THREE 1960 TEST ROADS

Supplier Number	1	2	3
Flash Point COC°F	585	525	615
Softening Point R and B °F	115	115	119
Penetration—100 gr 5 sec 77°F	83	96	87
200 gr 60 sec 39.2°F	25	36	22
200 gr 60 sec 32°F	22	26	19
Penetration Ratio	30.2	37.5	25.3
Ductility at 77°F, 5 cm/min	150+	150+	128
Viscosity—Centistokes at 275°F	460	365	210
Centistokes at 210°F	3953	2763	1472
Thin Film Oven Test			
% loss by weight	0.1	0.3	0.0
Residue			
% Original Penetration at 77°F	67.5	60.4	61.0
Ductility at 77°F, 5 cm/min	150+	110	115
Solubility in n-hexane			
% asphaltenes	19.7	24.7	18.8
Penetration Index*	−0.77	−1.17	−1.64

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* Calculated by interpolation in Figure 30 on basis of penetration at 77°F and Newtonian viscosity at 140°F obtained by extrapolation from viscosity measurements made at higher temperatures.

TABLE II

1968 INSPECTION DATA ON PAVEMENT SAMPLES FROM ONTARIO'S THREE 1960 TEST ROADS

Test Road Number	1			2			3		
Asphalt Supplier	1	2	3	1	2	3	1	2	3
Year Test Road Constructed	1960	1960	1960	1960	1960	1960	1960	1960	1960
Asphalt Cement, Grade (Original)	85/100	85/100	85/100	85/100	85/100	85/100	85/100	85/100	85/100
Asphalt Content, Per Cent (Recovered) *	6.59	5.94	5.6	6.93	6.2	5.52	6.65	5.55	5.64
Sieve Analysis of Recovered Aggregate									
Pass 3/4 inch	100	100	100	100	100	100	100	100	100
Pass 1/2 inch	93.2	97.5	96.3	98.1	96.7	95.8	94.3	94.1	93.5
Pass 3/8 inch	78.6	81.8	79.0	86.2	82.5	82.1	79.2	82.4	76.5
Pass No. 4 Sieve	53.7	56.9	53.0	58.5	53.6	53.6	53.9	59.7	56.8
Pass No. 8 Sieve	45.4	47.3	44.2	45.8	42.4	42.8	44.7	47.9	46.8
Pass No. 16 Sieve	40.3	40.9	38.7	39.0	35.9	35.9	36.1	39.4	37.7
Pass No. 30 Sieve	32.5	31.4	29.9	27.7	26.1	25.8	22.3	24.3	21.9
Pass No. 50 Sieve	18.8	18.1	18.1	11.8	12.5	11.4	8.6	9.7	8.6
Pass No. 100 Sieve	7.0	8.6	7.9	4.4	4.8	4.6	3.1	4.4	4.5
Pass No. 200 Sieve	4.1	6.2	4.9	2.8	3.1	3.2	1.7	3.1	3.4
Spec. Grav. and Absorption Recovered Aggregate									
ASTM Bulk Specific Gravity	2.654	2.652	2.654	2.681	2.682	2.682	2.627	2.627	2.627
ASTM Apparent Specific Gravity	2.765	2.763	2.765	2.775	2.778	2.778	2.727	2.728	2.728
Virtual Specific Gravity	2.725	2.710	2.687	2.729	2.706	2.720	2.711	2.702	2.692
Water Absorption, Wt. %	1.5	1.5	1.5	1.2	1.26	1.26	1.40	1.41	1.40
Asphalt Absorption, Wt. %	1.0	0.82	0.47	0.66	0.34	0.53	1.2	1.1	0.94
Inspection Data on Pavement Sample									
Marshall Stability (recompacted) **	2800	3200	2650	2525	2550	2700	2550	3450	2790
Flow Index (recompacted) **	16	16	15	12	15	9	12	10	11
% Air Voids (as received)	1.0	2.0	1.2	2.1	1.1	4.3	2.7	5.9	5.4
% Air Voids (recompacted) **	1.4	1.2	0.7	0.2	0.6	3.3	1.5	4.0	2.4
% Laboratory compacted density as received	100.4	99.5	99.3	98.1	99.5	98.9	98.8	98.0	96.9
% Voids in Mineral Aggregate (recompacted) **	14.8	12.9	13.6	15.2	14.6	15.1	14.5	14.6	13.7

* by weight of total mix
** 60 blows Marshall Mechanical Compactor.

TABLE 12

1968 INSPECTION DATA ON ORIGINAL AND ON RECOVERED ASPHALT CEMENTS FROM ONTARIO'S THREE 1960 TEST ROADS

Test Road Number	Asphalt Supplier	Transverse Cracks per Mile				Penetration Test				Penetration Ratio	Viscosity at 275°F		Newtonian Viscosity at 140°F by Extrapolation*		Ductility cm.		Penetration Index**	
		Types				Original Asphalt	Recovered Asphalt			Recovered Asphalt	Original Asphalt	Recovered Asphalt	Original Asphalt	Recovered Asphalt	Recovered Asphalt		Original Asphalt	Recovered Asphalt
		1	2	3	4	77°F 100 g. 5 sec.	77°F 100 g. 5 sec.	39.2°F 200 g. 60 sec.	32°F 200 g. 60 sec.	$\frac{39.2}{77}$ x 100	cs	cs	poises	poises	77°F 5 cm/min.	39.2°F 1 cm/min.		
1	1	12	19	28	13	83	33	14	11	42.4	460	867	1,478	7,430	150	3.3	-0.77	-0.42
	2	19	54	124	91	96	37	18	14	48	365	758	813	9,920	92	4.9	-1.17	+0.42
	3	227	95	307	71	87	33.5	17	13.5	50.7	210	434	392	2,680	27	0.0	-1.64	-1.33
2	1	3	1	3	2	83	32	14	11.5	43.8	460	849	1,478	6,345	150	4.3	-0.77	-0.69
	2	8	4	17	14	96	46	22	18.5	40.2	365	669	813	7,240	122	5.6	-1.17	+0.45
	3	62	18	52	29	87	28	12.5	10.5	44.6	210	564	392	6,440	10.5	0.0	-1.64	-0.89
3	1	1	-	1	-	83	40	20	14	50	460	720	1,478	5,050	150	2.6	-0.77	-0.56
	2	2	1	2	2	96	32	16	13	50	365	860	813	14,880	81	0	-1.17	+0.87
	3	46	12	73	4	87	32.5	16.5	13	46.7	210	460	392	3,460	23.5	0	-1.64	-1.20

* Obtained by extrapolation if necessary from viscosity measurements made at higher temperatures.

** Calculated by interpolation in Figure 30 on basis of extrapolated Newtonian viscosity at 140°F and penetration at 77°F.

TABLE 13

VISCOSITY-TEMPERATURE (PENETRATION INDEX) CHARACTERISTICS OF SOME COMMERCIAL ASPHALTS

		1	2	3	4	5	6	7	8	9	10	11	12
Penetration at 77°F, 100 gr. 5 sec.		250	85	60	265	79	79	165	84	747	418	414	627
Softening Point(Ring and Ball) °F		96.5	116.5	121	113	121	121	107.5	121	114.5	99	98	109.5
Penetration at S.P., 100 gr. 5 sec.		640	630	820	1875	590	1450	680	615	4500	1140	1100	2750
^{1}Viscosity poises at S.P.		7.5×10^3	7.0×10^3	3.8×10^4	2.2×10^3	3.8×10^4	1.1×10^4	1.0×10^4	1.0×10^4	3.91×10^4	3.55×10^3	5.71×10^3	5.22×10^2
Temperature for 800 penetration, °F		101	121	120.5	96.5	129	112	111	127	78	91	91	92.5
^{1}Viscosity poises at 800 penetration		5.3×10^3	4.8×10^3	3.8×10^4	1.2×10^4	1.8×10^4	3.0×10^4	8.0×10^3	6.0×10^3	9.05×10^2	9.13×10^3	1.27×10^4	2.71×10^4
^{1}Temperature for 12,000 poises, °F		92	111	126	96.5	134	120	106	118	88	88	91.5	86.5
^{2}Viscosity poises at 275°F		1.5	2.92	2.17	0.71	5.84	4.43	2.80	4.80	0.42	0.79	0.80	0.51
^{3}Viscosity poises at 140°F		2.95×10^2	1.17×10^3	9.38×10^2	1.02×10^2	7.6×10^3	2.44×10^3	8.40×10^2	2.27×10^3	26.2	82.5	92.2	27.3
Penetration Indices													
Based on S.P. (R and B)	1*	-1.0	-0.7	-0.9	+3.7	-0.2	-0.2	0.0	0.0				
	2**									+18.0	+3.9	+3.5	+13.2
Based on pen at S.P.	1*												
	2**	+0.4	+0.1	-1.0	-0.4	+0.8	-3.7	+0.7	+0.8	+0.4	+0.8	+0.6	+0.8
Based on temp.for 800 pen.	1*	+0.4	+0.1	-0.9	-0.5	+1.0	-1.6	+0.7	+1.0				
	2**									-1.8	+0.7	+0.6	+1.0
Based on temp.for 12,000 poises	1*	-2.6	-1.6	-0.2	-0.5	+1.6	-0.3	-0.4	-0.6				
	2**									+14.2	-0.93	+0.81	+2.44
Based on viscosity at 140°F		-0.8	-1.0	-1.5	-1.7	+3.7	-0.1	-0.1	-0.1	-1.8	-1.4	-1.3	-1.8

* Based on Heukelom's modification of Pfeiffer and Van Doormaal's nomograph.

** Based on Pfeiffer's and Van Doormaal's equations for Penetration Index.

Notes

1. Cannon Manning or Asphalt Institute vacuum capillary or American Oil Company cone and plate viscometer and obtained at a constant power input of 1000 ergs/sec/cc.
2. Zeitfuchs cross-arm viscometer.
3. Cannon Manning or Asphalt Institute vacuum capillary viscometer.

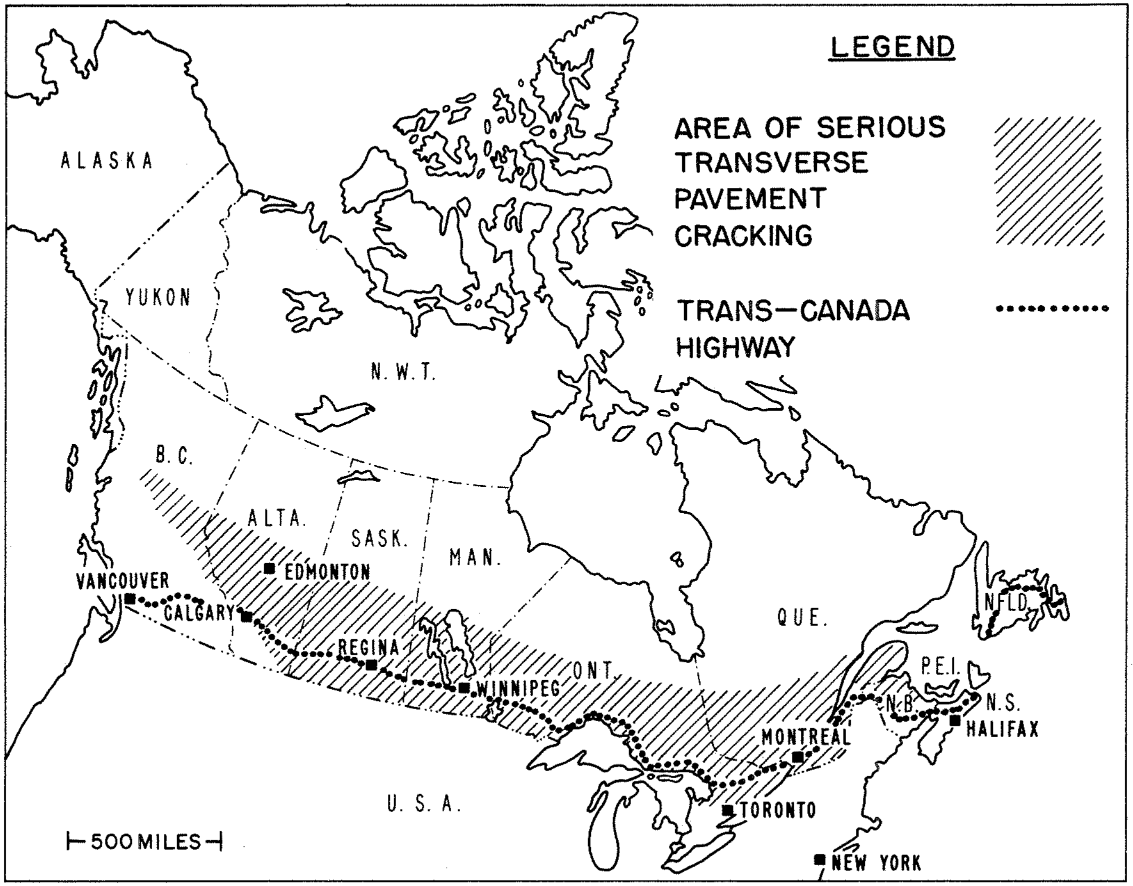


FIG. I MAP OF CANADA ILLUSTRATING WHERE TRANSVERSE PAVEMENT CRACKING IS A SERIOUS PROBLEM.

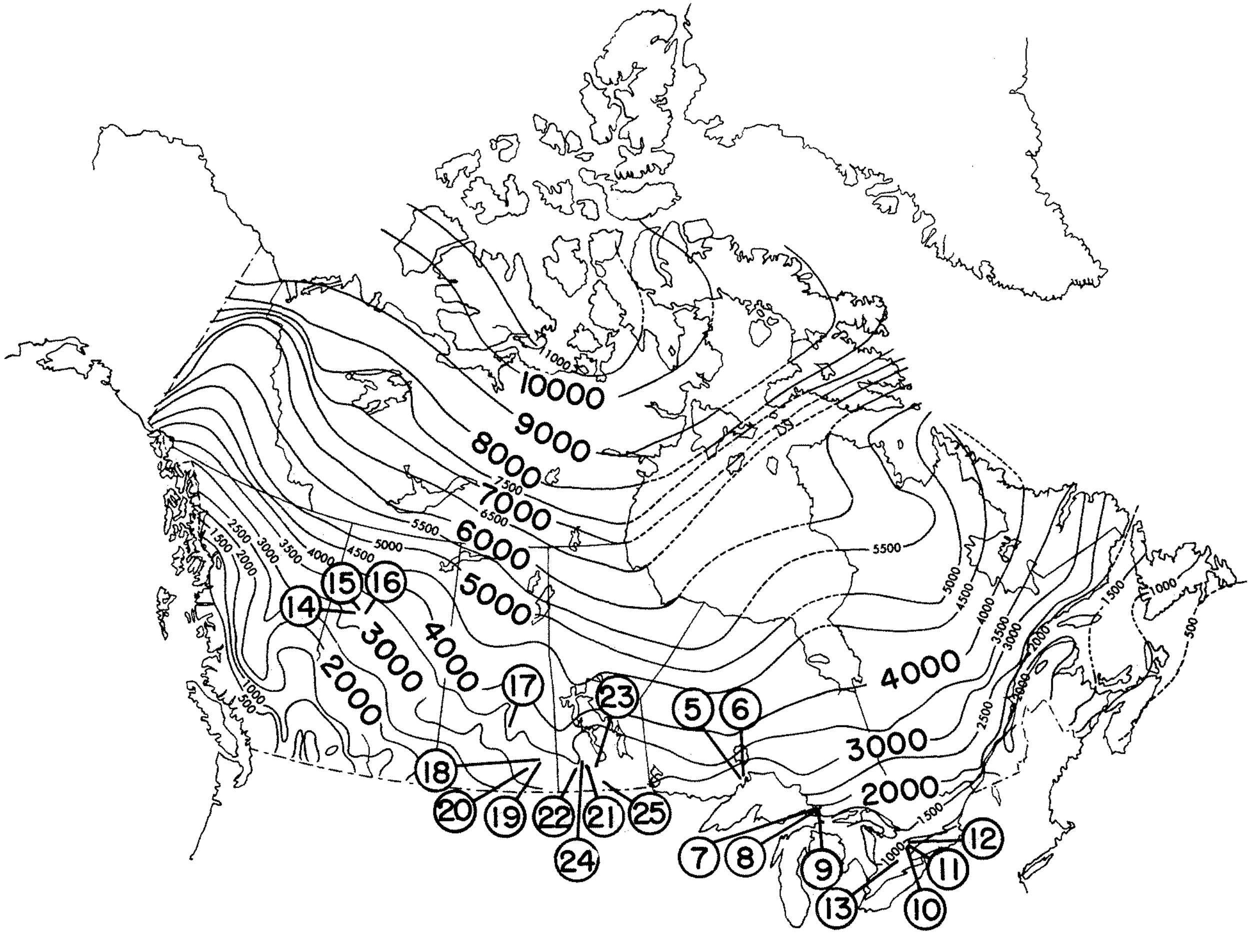
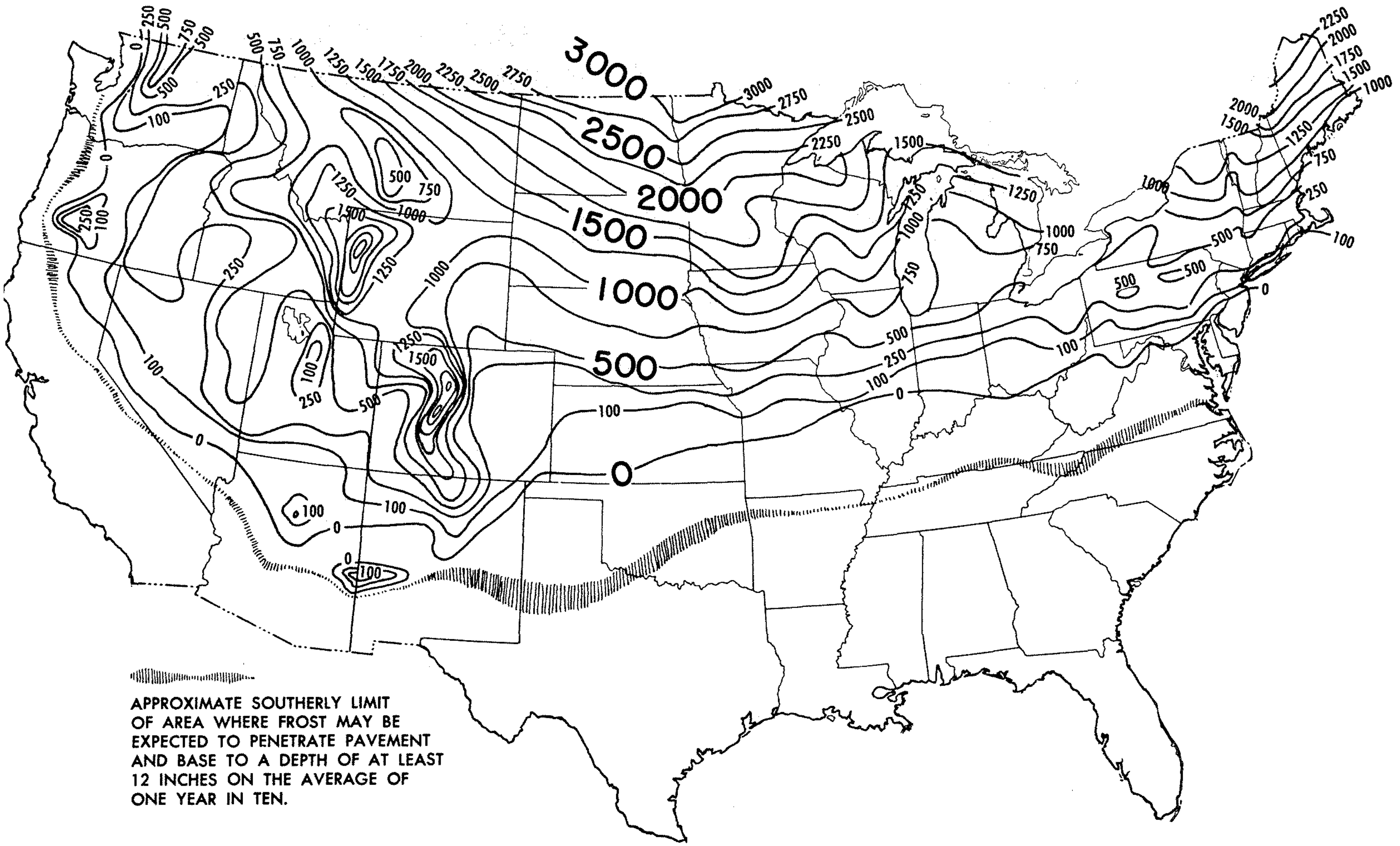


FIG. 2 MAP OF CANADA ILLUSTRATING FREEZING INDICES AND LOCATION OF FIGURES 5 TO 25



APPROXIMATE SOUTHERLY LIMIT OF AREA WHERE FROST MAY BE EXPECTED TO PENETRATE PAVEMENT AND BASE TO A DEPTH OF AT LEAST 12 INCHES ON THE AVERAGE OF ONE YEAR IN TEN.

FIG.3 FREEZING INDEX MAP OF THE UNITED STATES.

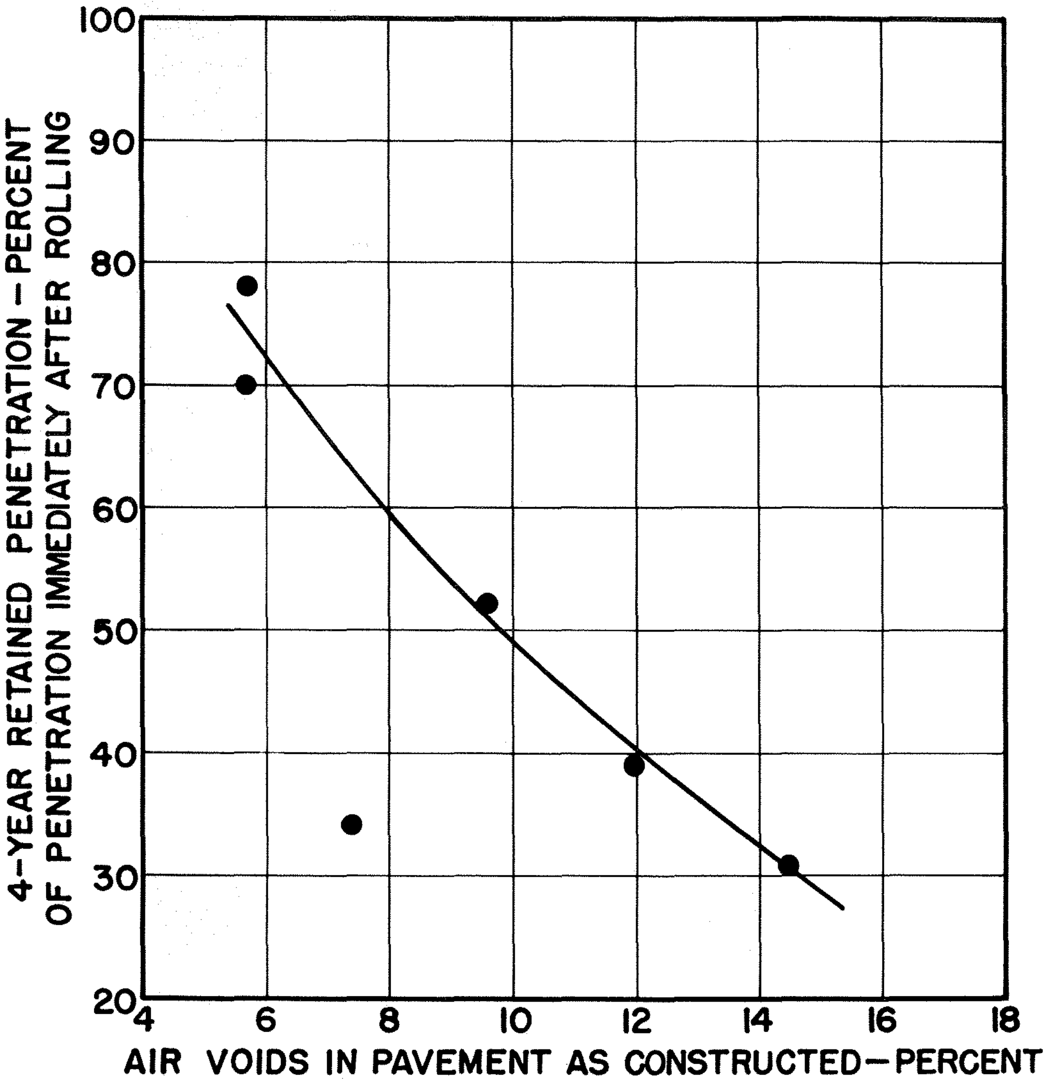


FIG. 4 EFFECT OF INITIAL AIR VOIDS IN PAVEMENT ON CHANGE IN PENETRATION OF ASPHALT AFTER FOUR YEARS OF SERVICE.

Figure 5 — 85/100 Penetration Pavement, located about 120 miles east of Port Arthur, Ontario, constructed in 1961.

Figure 6 — 150/200 Penetration Pavement, located about 110 miles east of Port Arthur, Ontario, constructed in 1960.

Figure 7 — 85/100 Penetration Pavement, located about 20 miles north of Sault Ste. Marie, Ontario, constructed in 1960.

Figure 8 — 150/200 Penetration Pavement, located about 30 miles north of Sault Ste. Marie, Ontario, constructed in 1962.

Figure 9 — 150/200 Penetration Pavement, located about 40 miles north of Sault Ste. Marie, Ontario, constructed in 1963.

Figure 10 — 85/100 Penetration Pavement, located west of Orangeville, Ontario. Four years old.

Figure 11 — 150/200 Penetration Pavement, located west of Orangeville, Ontario. Four years old.

Figure 12 — 85/100 Penetration Pavement in right lane, 150/200 Penetration Pavement in left lane, located west of Orangeville Ontario. Four years old.

Figure 13 — 85/100 Penetration Pavement, located west of Galt, Ontario. Four years old.

Figure 14 — 150/200 Penetration Pavement, located near Peace River, Alberta, constructed in 1963.

Figure 15 — Location near Peace River, Alberta. Transverse cracks extend through paved shoulders when main pavement and paved shoulders contain 150/200 or 200/300 penetration asphalt.

Figure 16 — Location near Peace River, Alberta. Transverse cracks in 150/200 or 200/300 penetration main pavement do not extend into the paved shoulder constructed with MC 2 or MC 3 liquid asphalt.

Figure 17 — 150/200 Penetration Pavement, located near Saskatoon, Saskatchewan, constructed in 1959.

Figure 18 — Bump has developed at each transverse crack in hot-mix pavement near Regina, Saskatchewan.

Figure 19 — Well-defined transverse cracks from 100 to 150 feet apart in pavement consisting of 16 inches of granular base and a surface treatment, located near Regina, Saskatchewan.

Figure 20 — Complete absence of periodic well-marked transverse cracks in SC 2 road mix ¾-inch thick laid directly on subgrade, located near Regina, Saskatchewan.

Figure 21 — 150/200 Penetration Pavement, located near Portage La Prairie, Manitoba, constructed in 1960.

Figure 22 — 150/200 Penetration Pavement, located near Brandon, Manitoba, constructed in 1963.

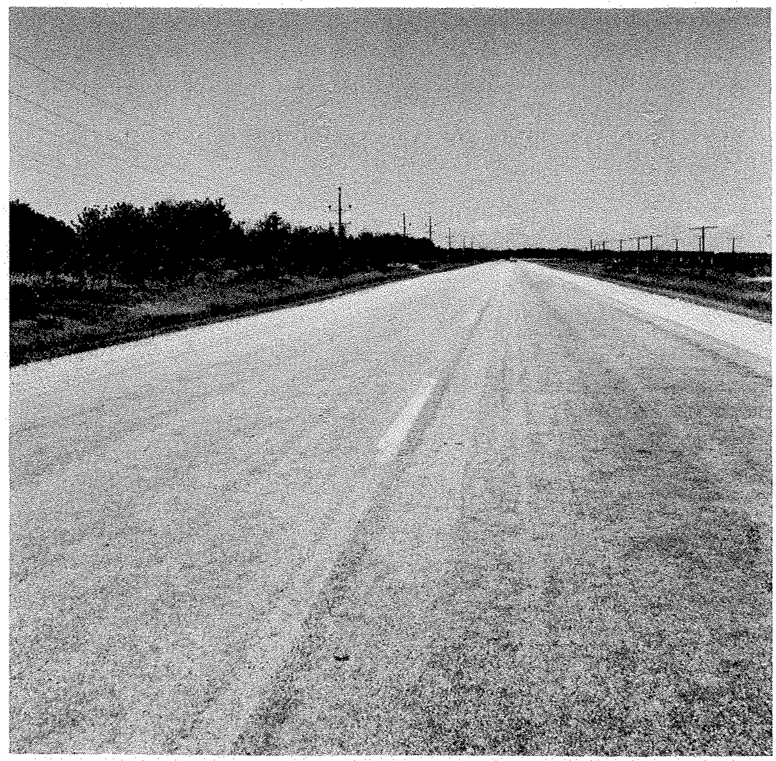


Figure 23 — 300/400 Penetration (SC 6) Pavement, located near Portage la Prairie, Manitoba, constructed in 1952.

Figure 24 — 300/400 Penetration (SC 6) Pavement, located near Neepawa, Manitoba, constructed in 1965.

Figure 25 — SC 3000 (SC 5) Pavement, located near Morden, Manitoba, constructed in 1965.

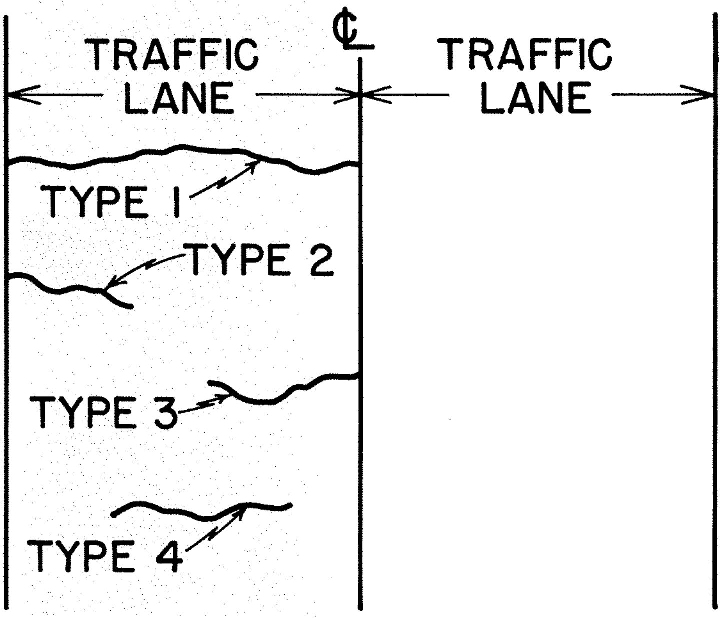


FIG. 26 TYPES OF TRANSVERSE PAVEMENT CRACKS.

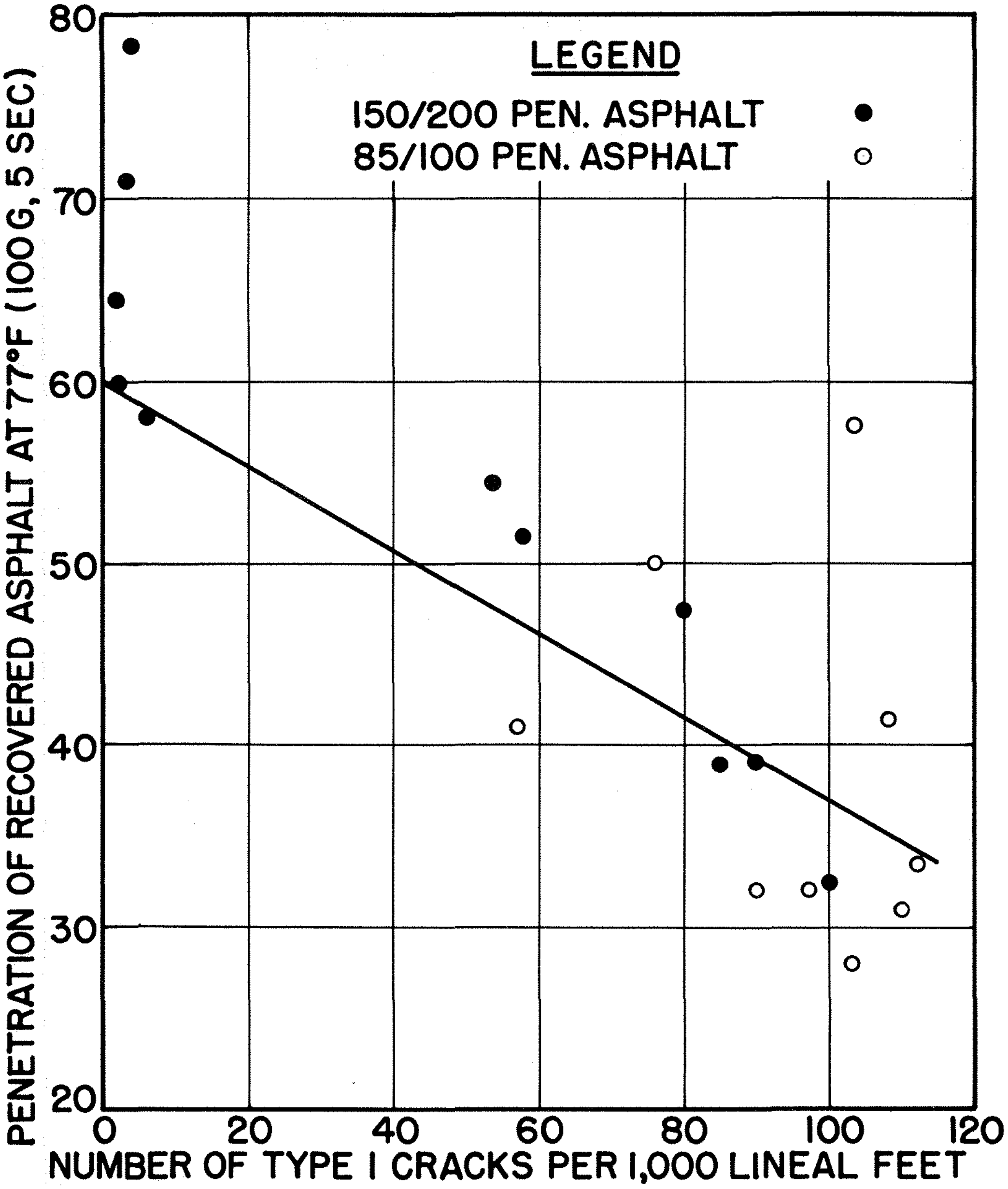


FIG. 27 RELATIONSHIP BETWEEN TYPE I TRANSVERSE PAVEMENT CRACKING AND PENETRATION AT 77°F OF RECOVERED ASPHALT.

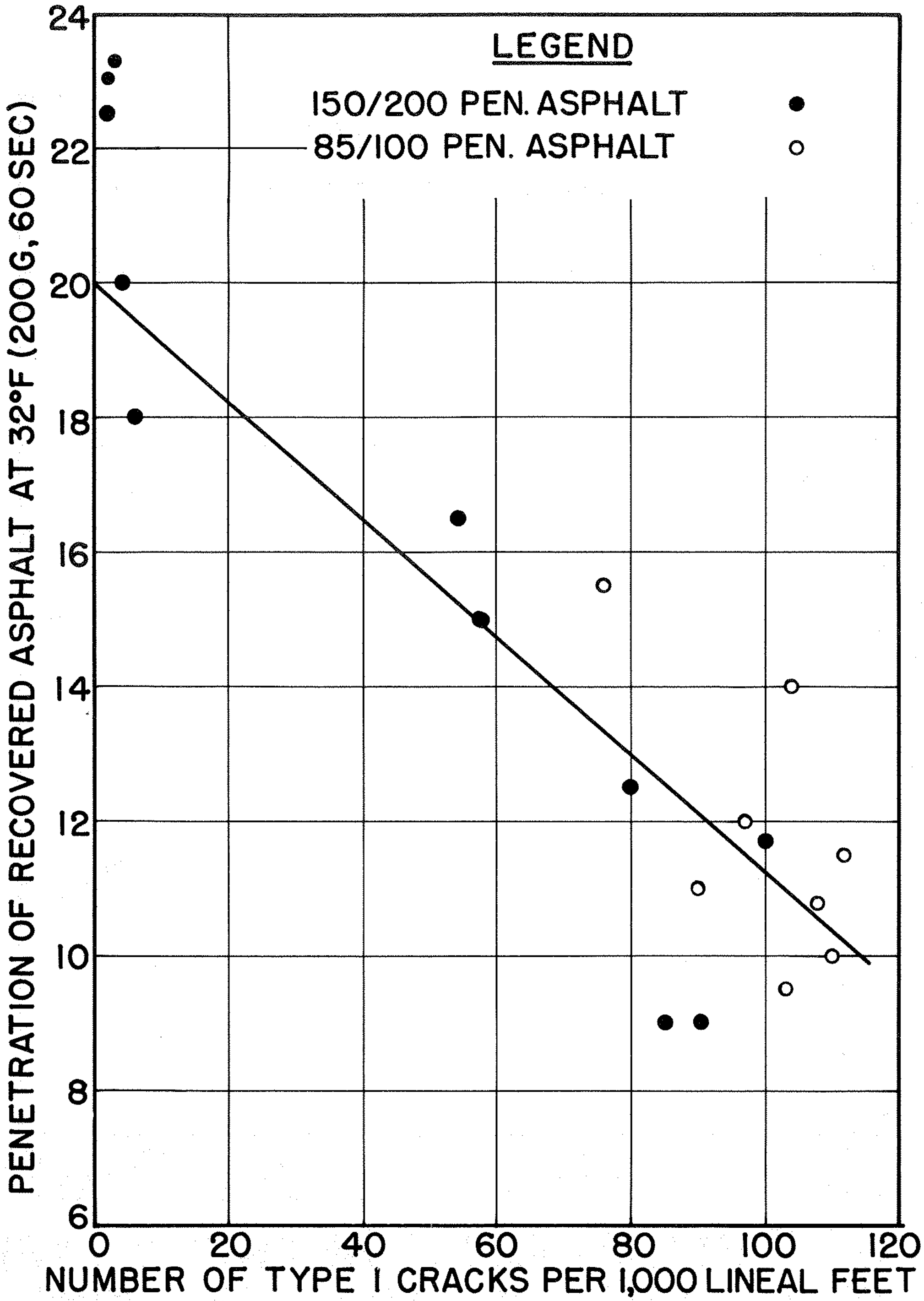


FIG. 28 RELATIONSHIP BETWEEN TYPE I TRANSVERSE PAVEMENT CRACKING AND PENETRATION AT 32°F OF RECOVERED ASPHALT.

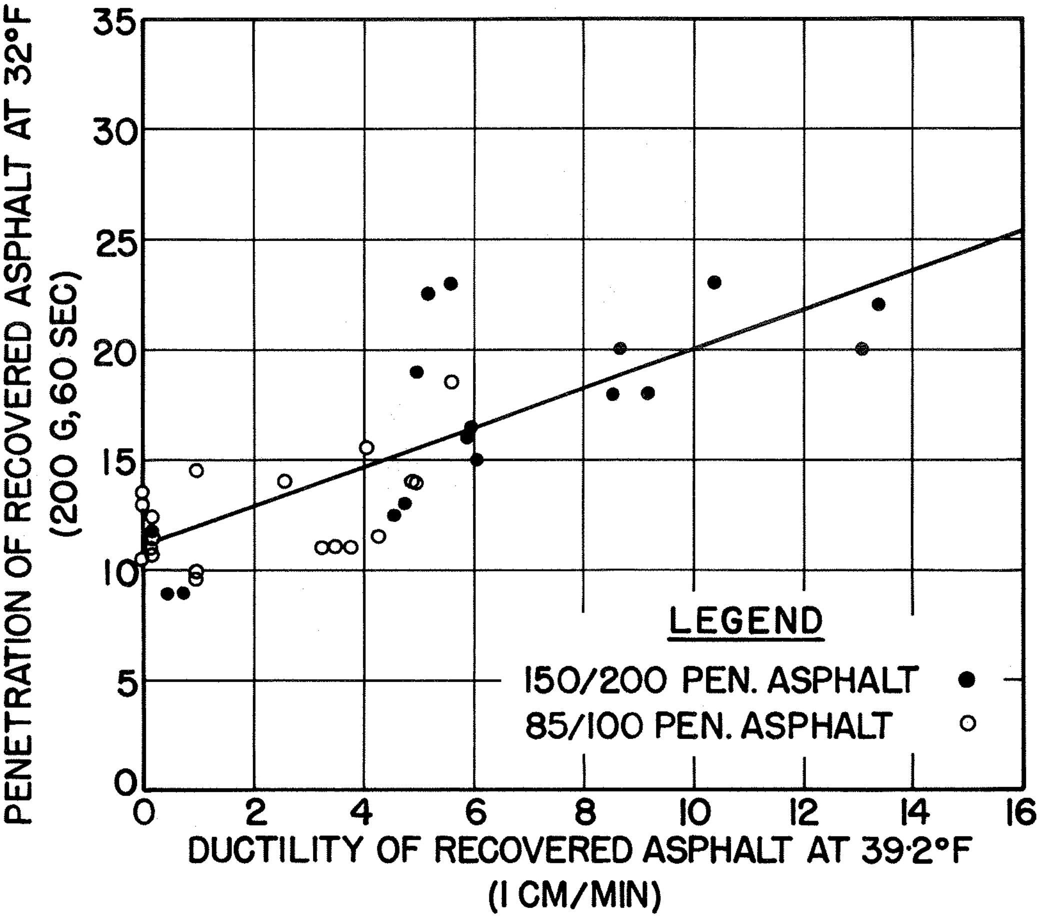


FIG.29 RELATIONSHIP BETWEEN PENETRATION AT 32°F AND DUCTILITY AT 39·2°F FOR RECOVERED ASPHALTS.

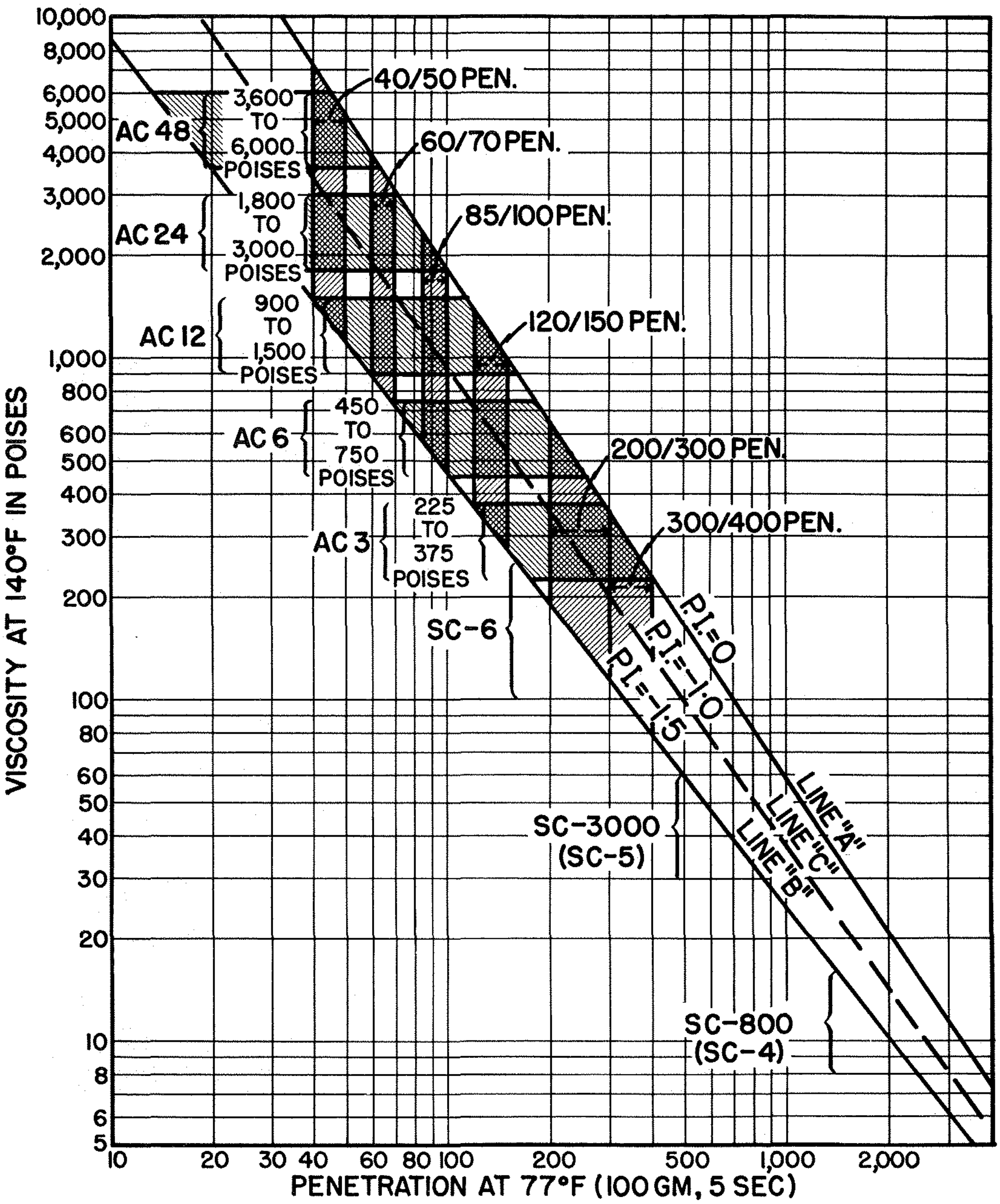


FIG. 30 CORRELATION BETWEEN VISCOSITY AT 140°F AND PENETRATION AT 77°F.

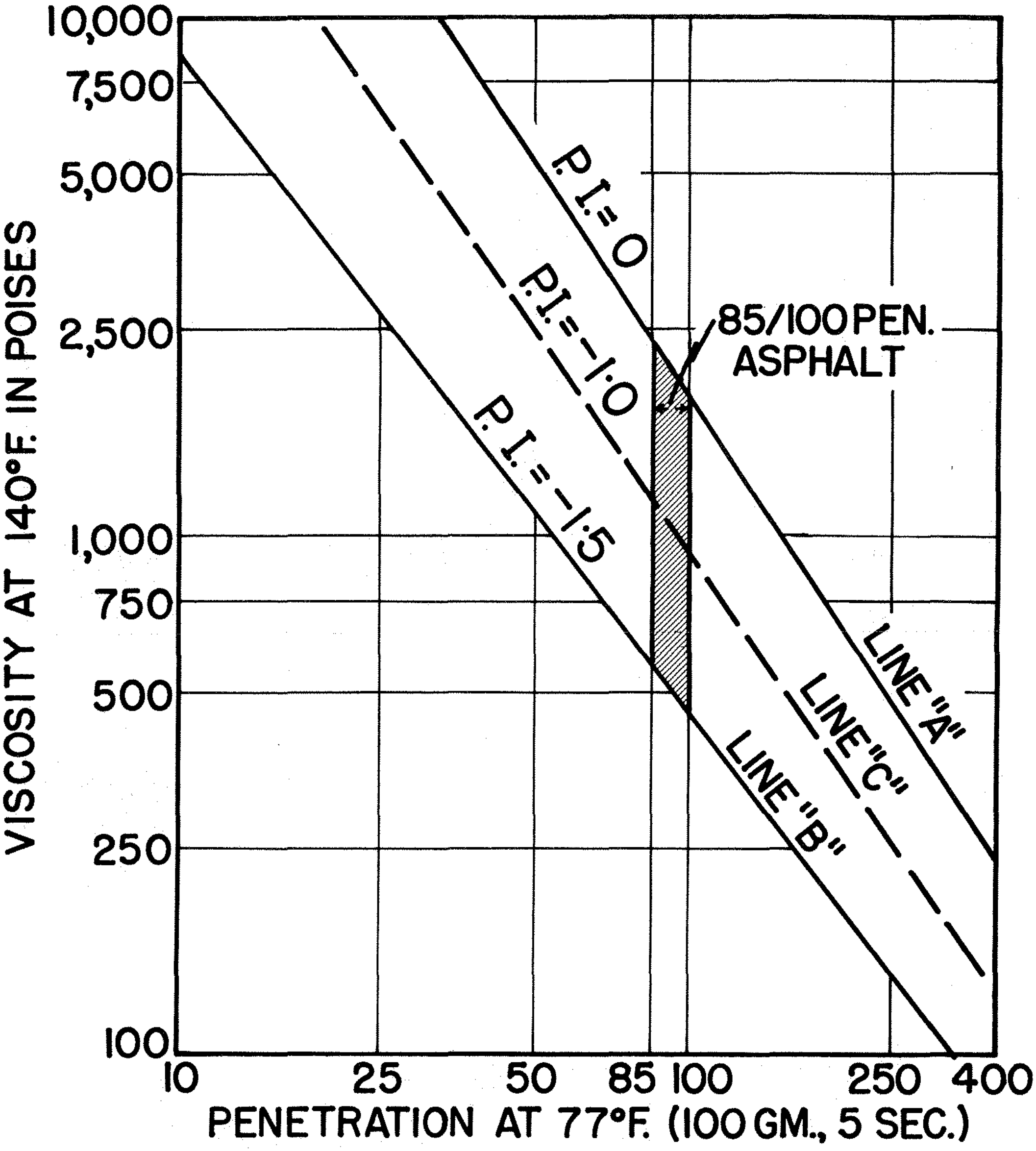


FIG. 31 CORRELATION BETWEEN 85/100 PENETRATION ASPHALT AND VISCOSITY AT 140°F. FOR CURRENTLY USED ASPHALT CEMENTS.

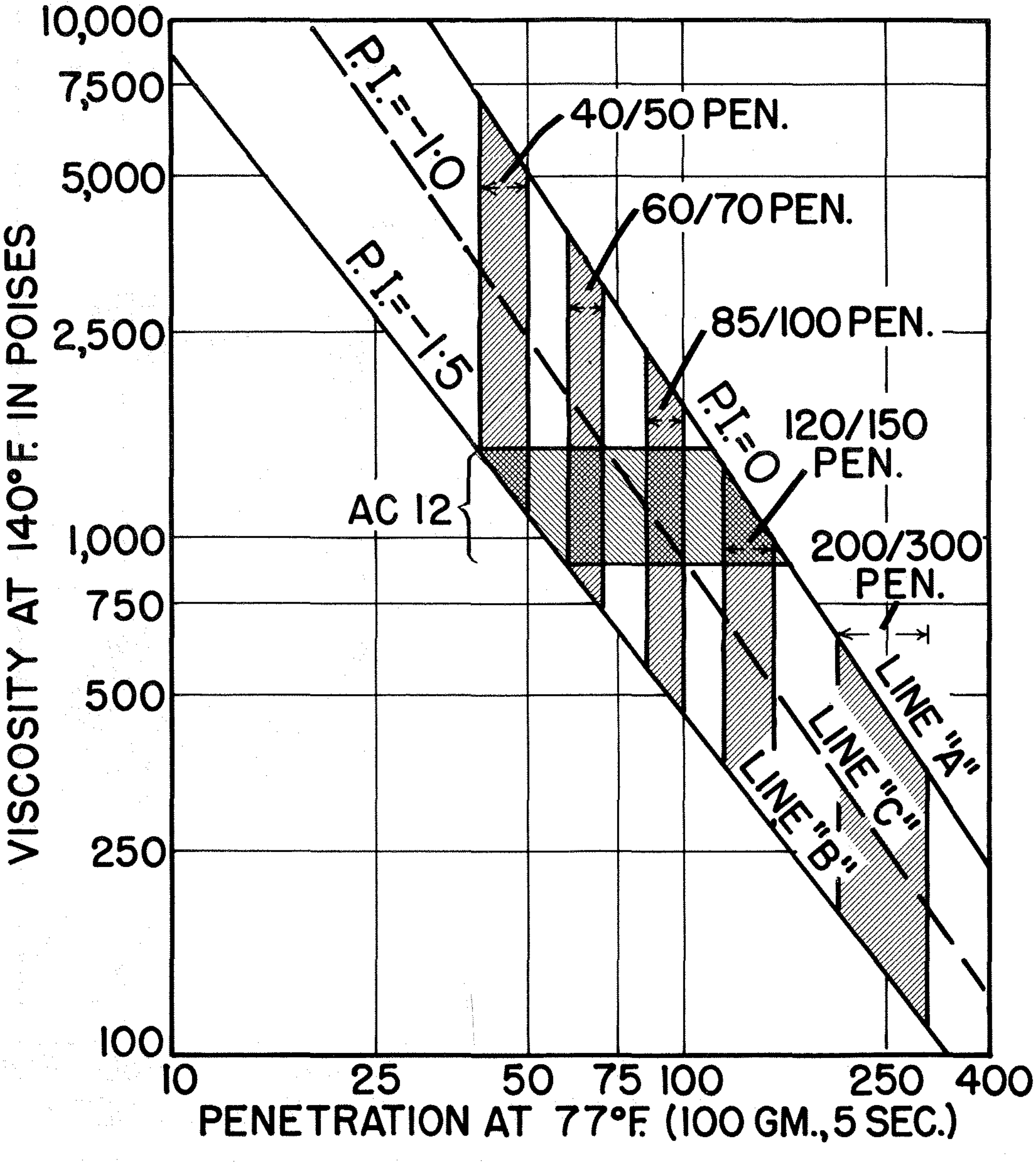


FIG. 32 CORRELATION BETWEEN AC12 AND PENETRATION AT 77° F. FOR CURRENTLY AVAILABLE ASPHALT CEMENTS.

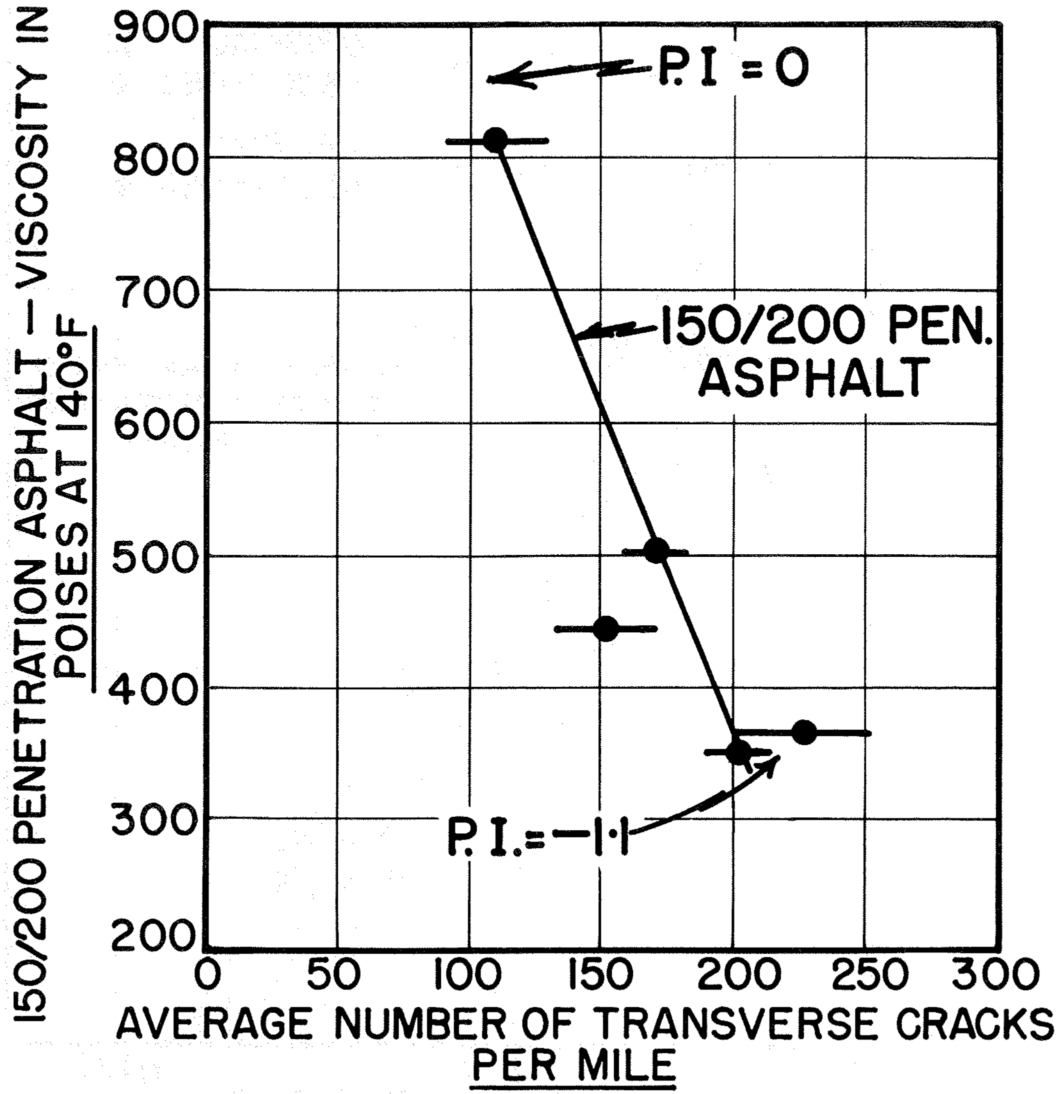


FIG. 33 RELATIONSHIP BETWEEN VISCOSITY AT 140°F OF 150/200 PENETRATION ASPHALTS AND TRANSVERSE PAVEMENT CRACKING.

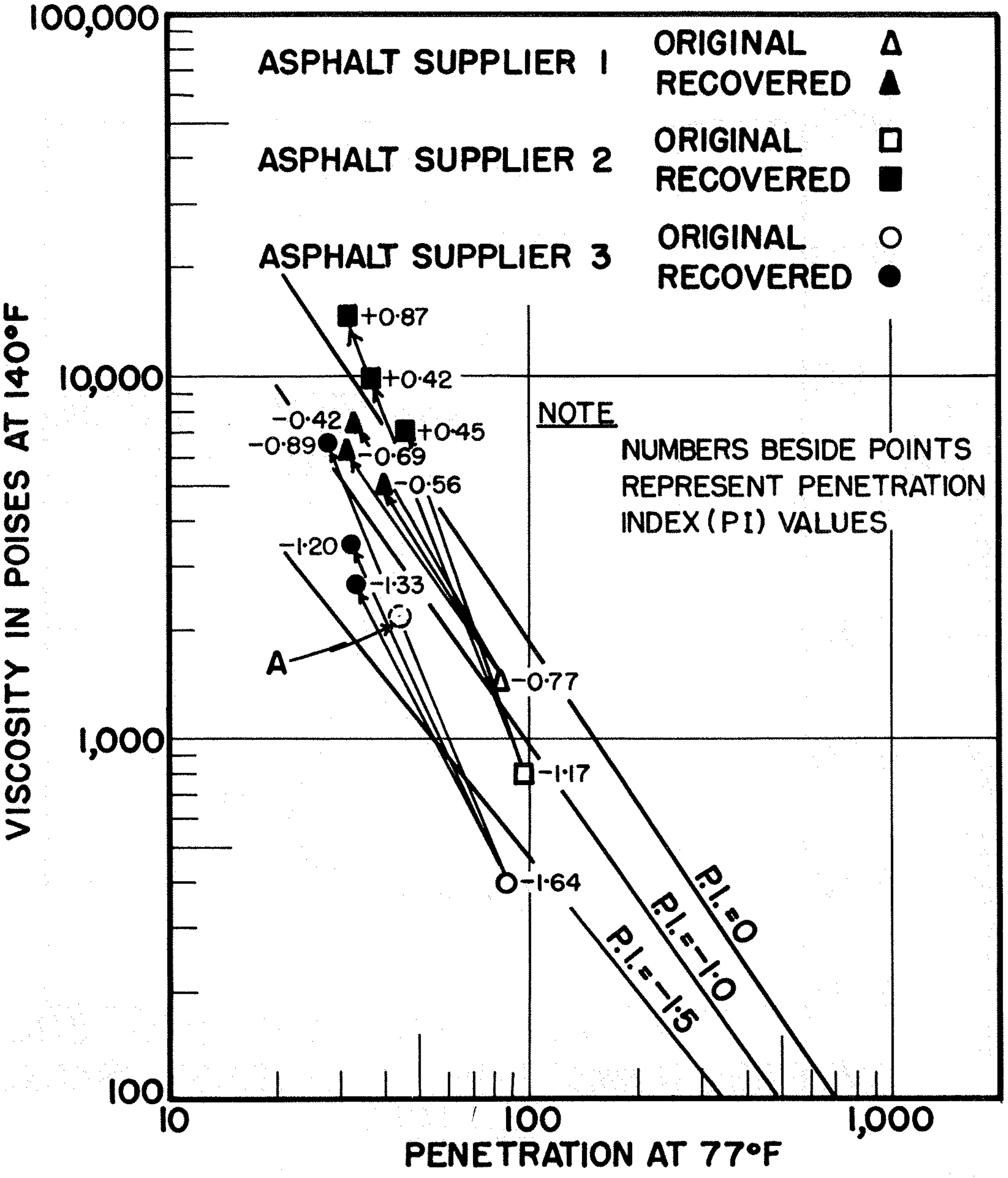


FIG. 34 COMPARISON OF PENETRATION INDICES OF ORIGINAL ASPHALT CEMENTS (85/100 PENETRATION) WITH PENETRATION INDICES OF SAME ASPHALT CEMENTS (30/40 PENETRATION) RECOVERED AFTER 8 YEARS IN SERVICE.

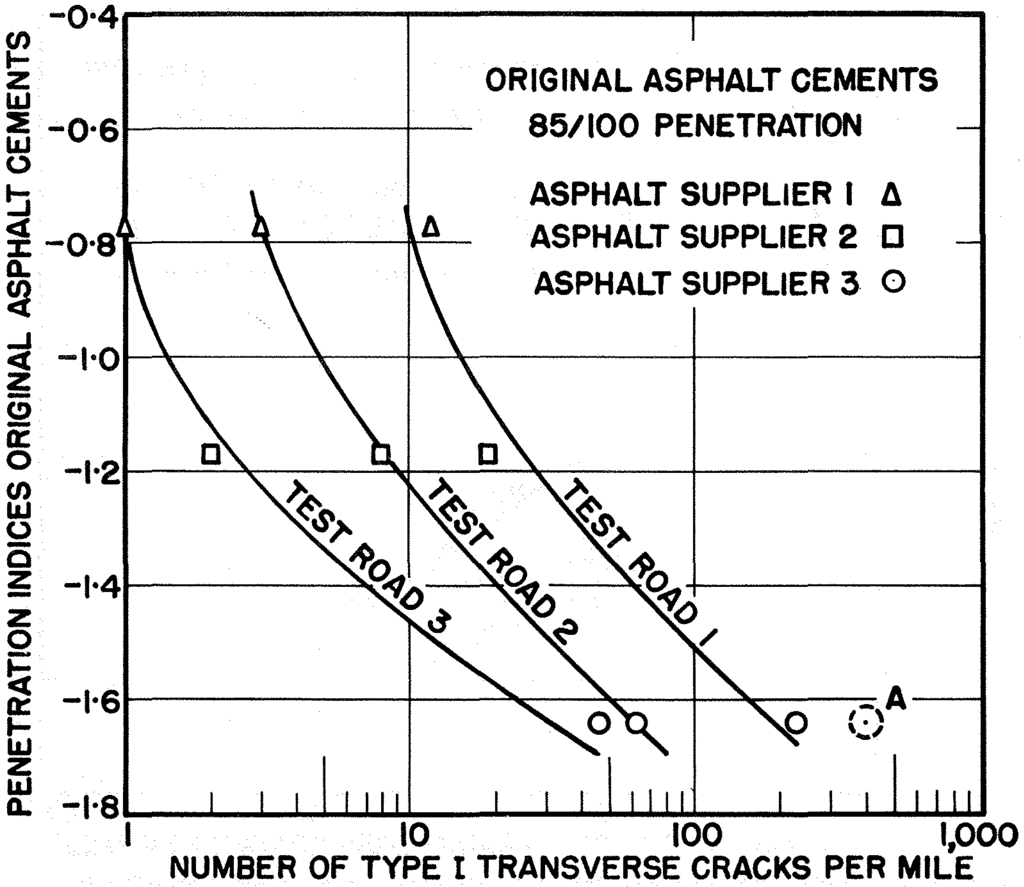


FIG. 35 RELATIONSHIP BETWEEN PENETRATION INDICES OF ORIGINAL 85/100 PENETRATION ASPHALT CEMENTS VERSUS NUMBER OF TYPE I TRANSVERSE PAVEMENT CRACKS PER MILE AFTER 8 YEARS OF SERVICE.

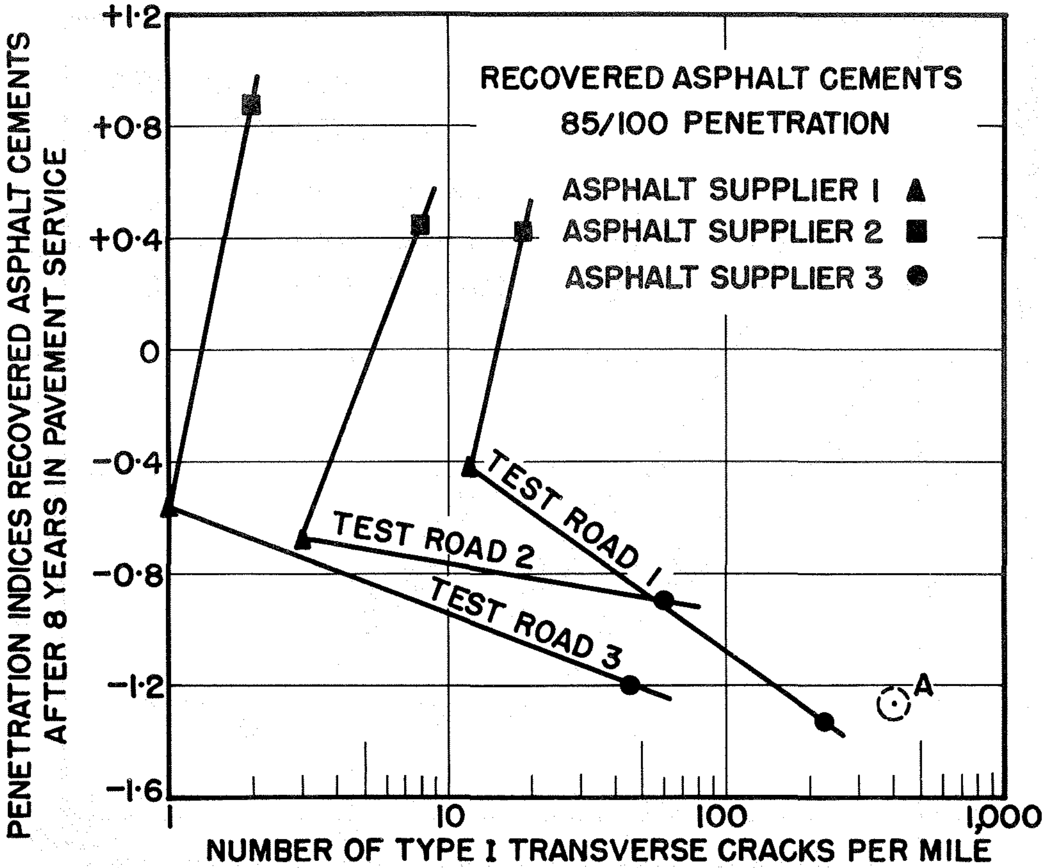


FIG.36 RELATIONSHIP BETWEEN PENETRATION INDICES OF RECOVERED ASPHALT CEMENTS (30/40 PENETRATION) VERSUS NUMBER OF TYPE I TRANSVERSE PAVEMENT CRACKS PER MILE AFTER 8 YEARS OF SERVICE.

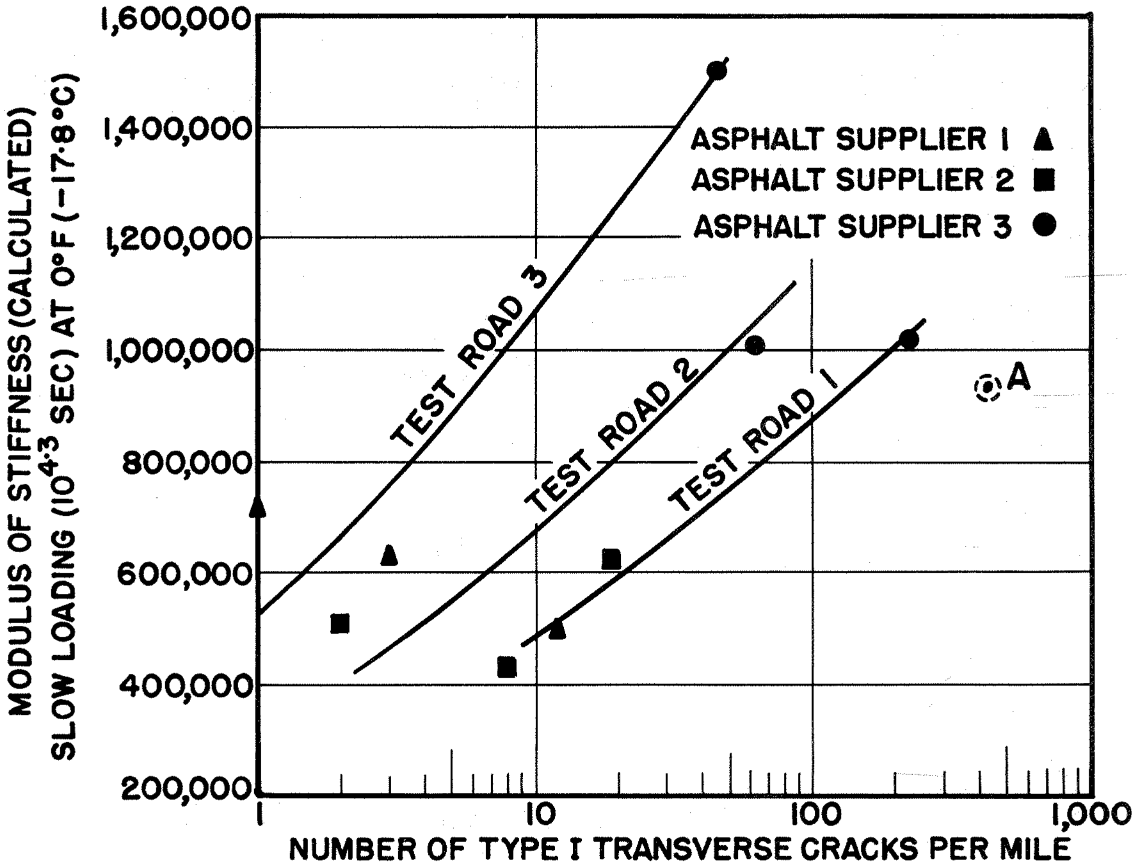


FIG. 37 INFLUENCE OF MODULI OF STIFFNESS (CALCULATED) OF 8-YEAR OLD TEST PAVEMENTS ON NUMBER OF TYPE I TRANSVERSE CRACKS PER MILE.

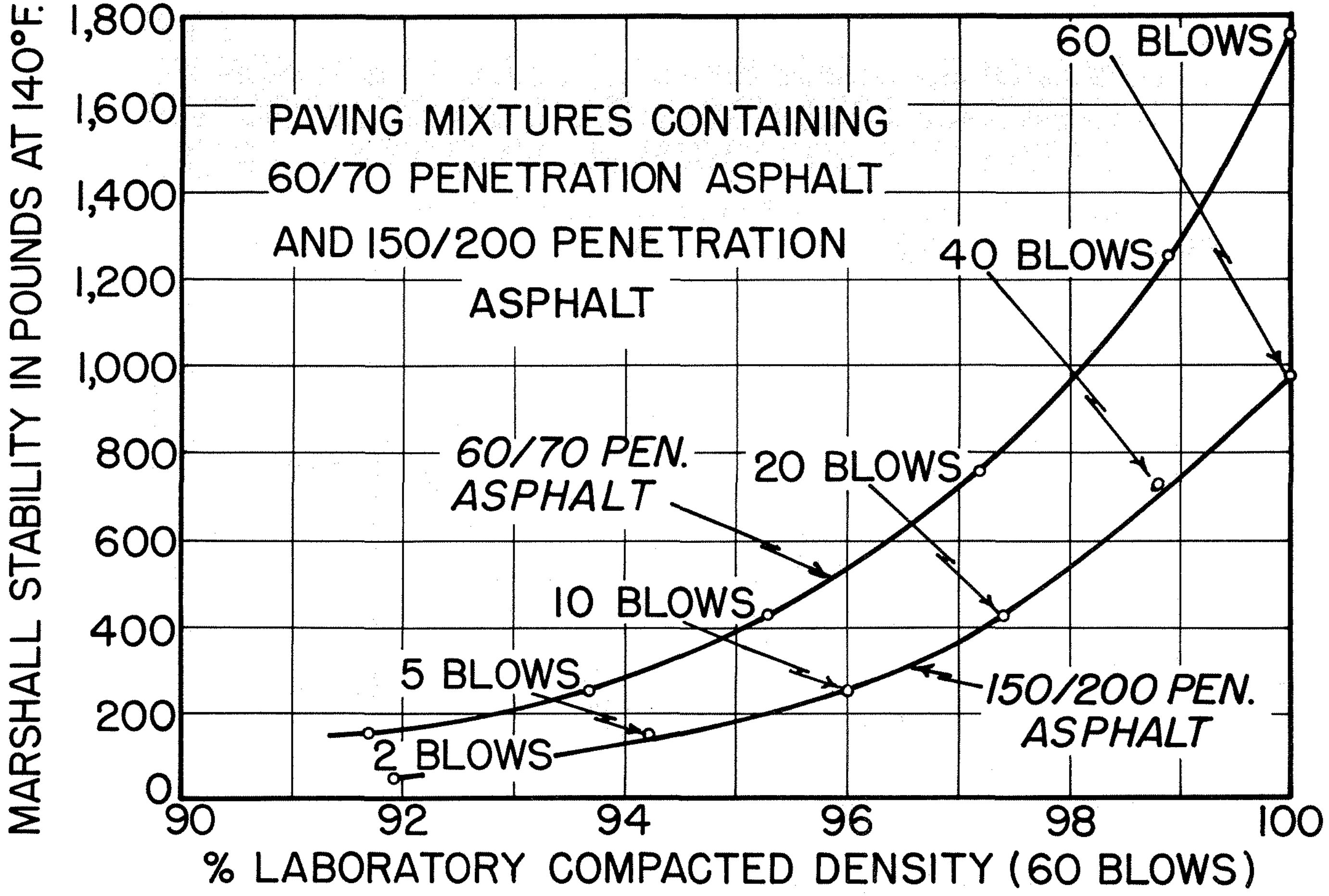
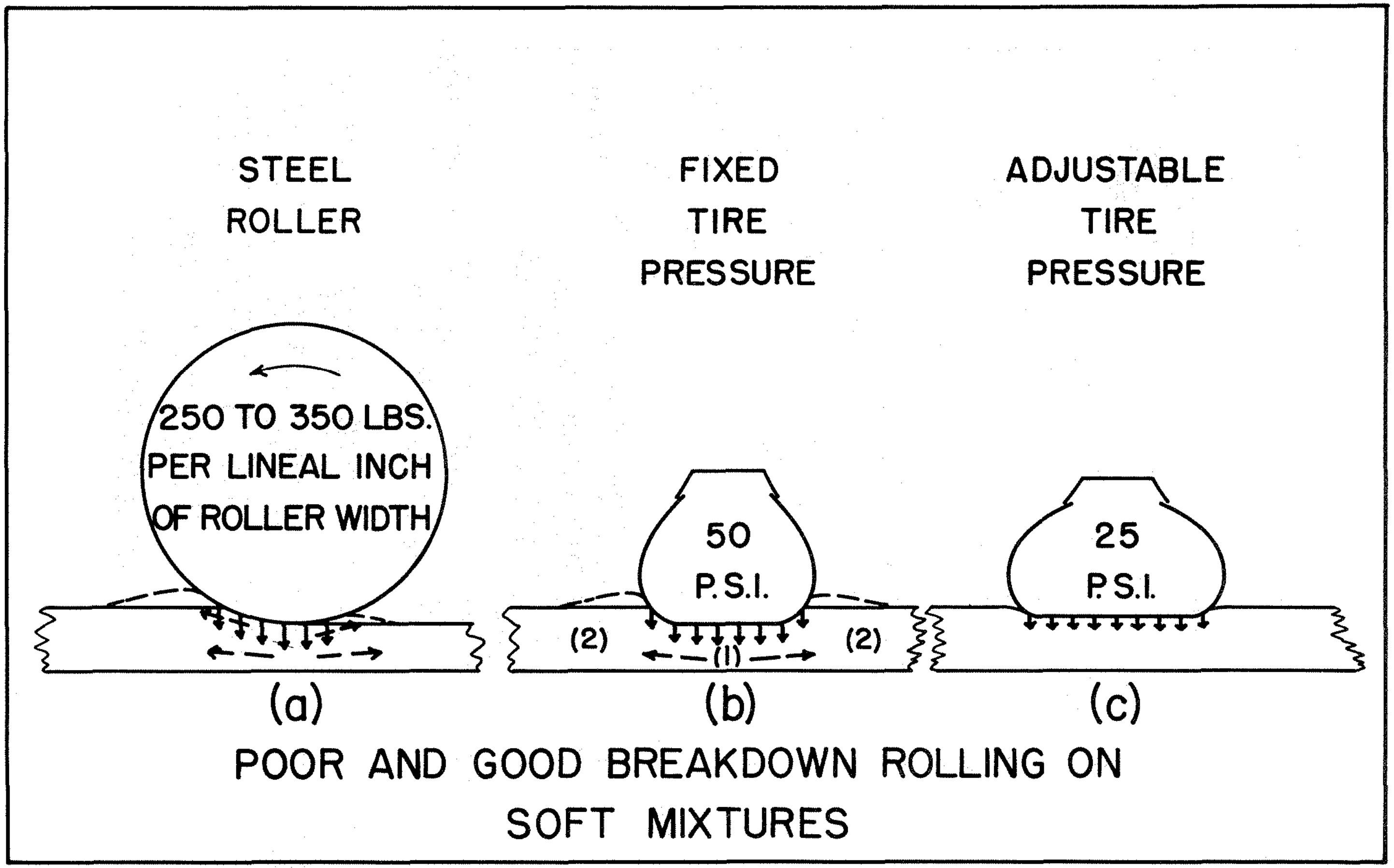


FIG. **38** ILLUSTRATING MARSHALL STABILITY VERSUS PERCENT LABORATORY COMPACTED DENSITY.



POOR AND GOOD BREAKDOWN ROLLING ON SOFT MIXTURES

FIG. 39 COMPARISON OF ACTION OF THREE TYPES OF ROLLERS FOR BREAKDOWN ROLLING OF RELATIVELY SOFT PAVING MIXTURES.

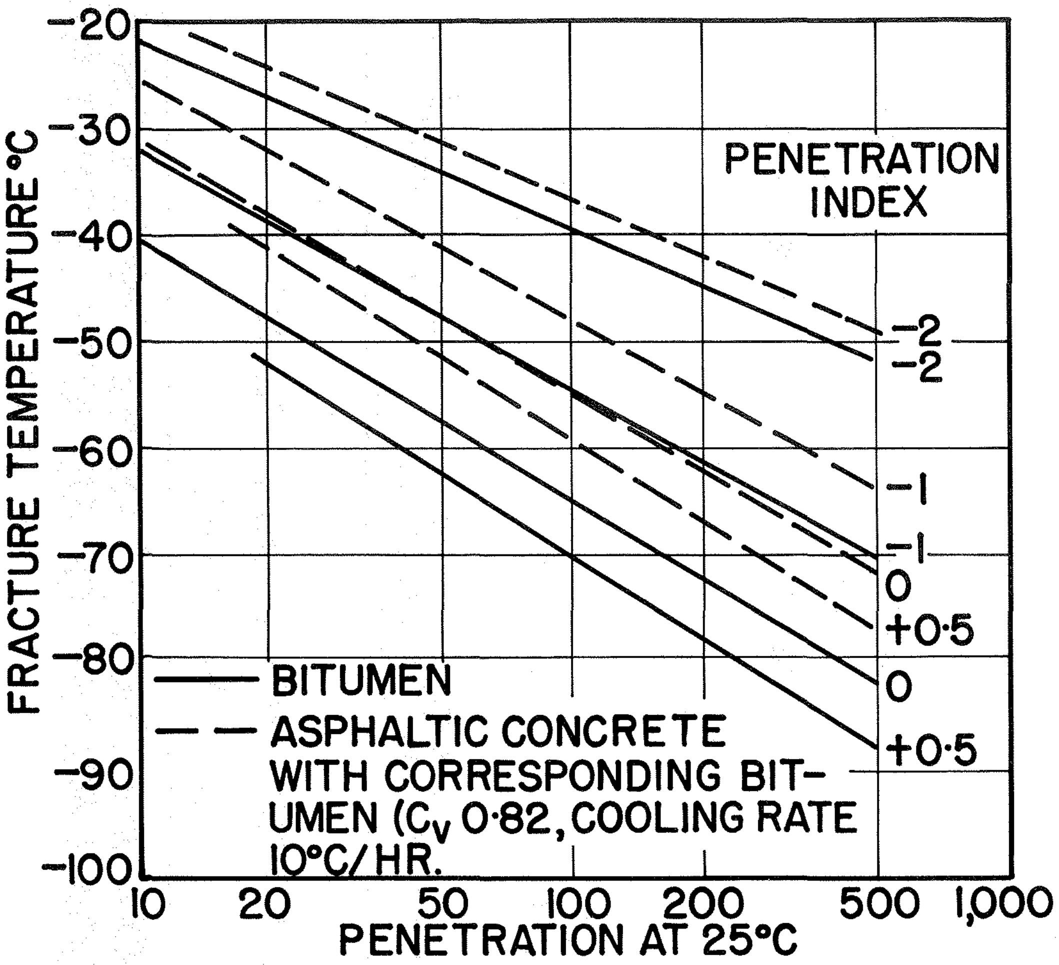


FIG. 40 INFLUENCE OF THE PENETRATION AND TEMPERATURE SUSCEPTIBILITY OF BITUMEN ON THE FRACTURE TEMPERATURE OF BITUMEN AND AN ASPHALTIC CONCRETE

(COURTESY HILLS AND BRIEN)

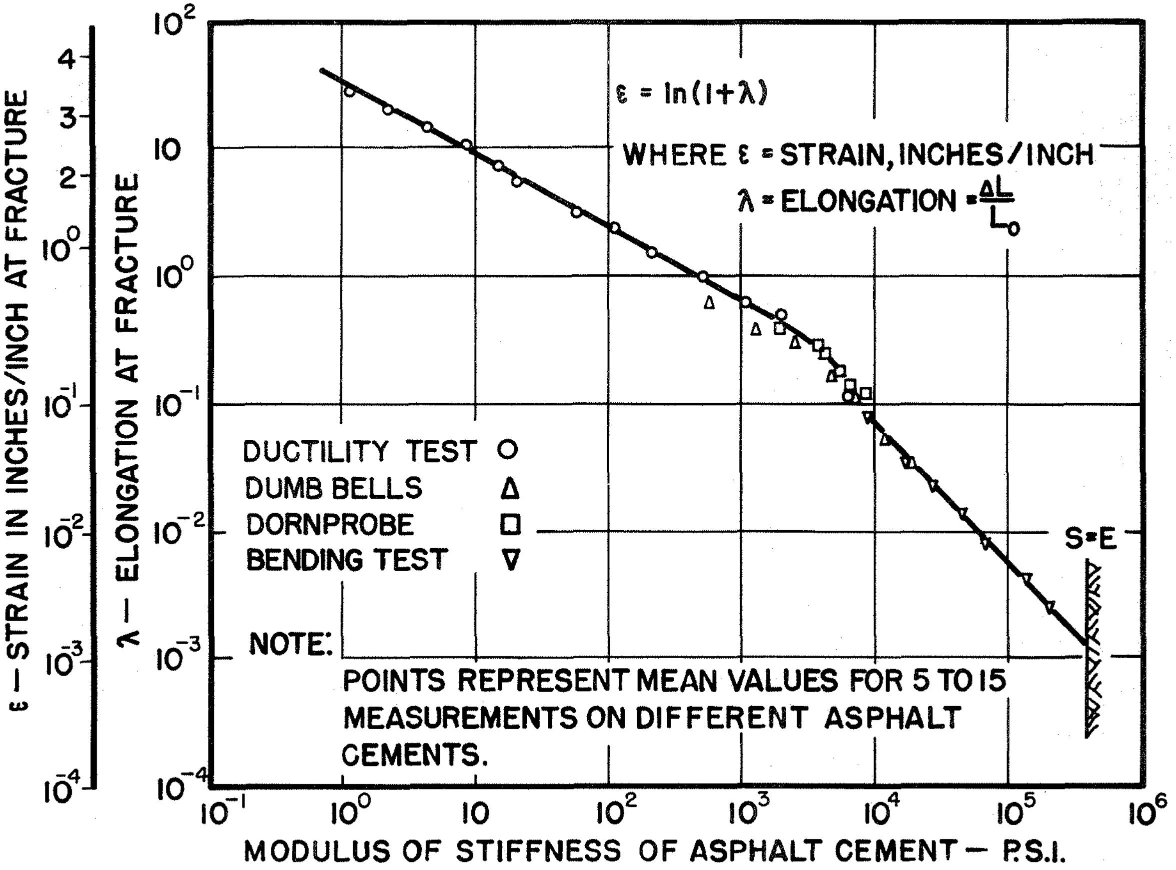
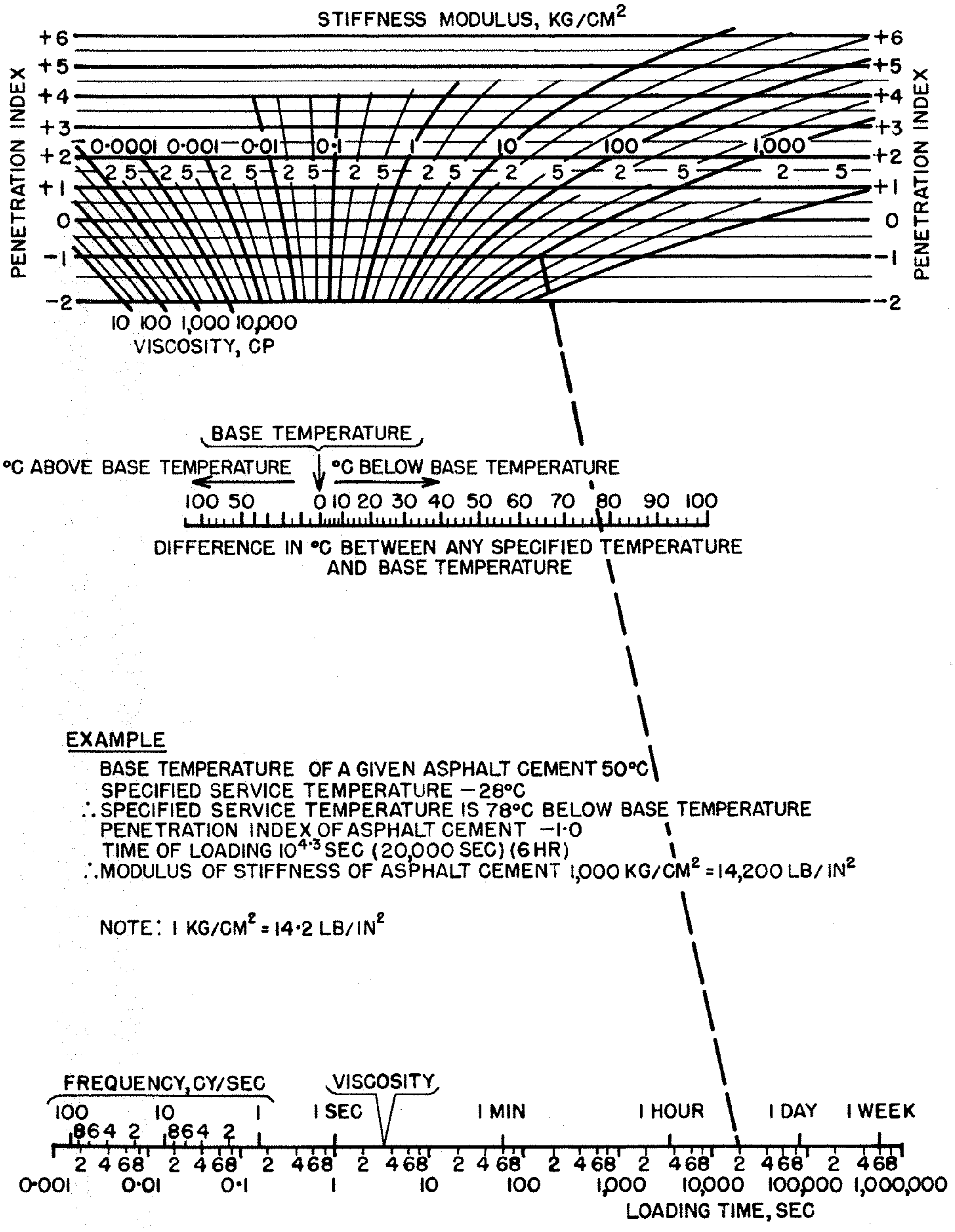


FIG. 41 INFLUENCE OF MODULUS OF STIFFNESS OF ASPHALT CEMENTS ON STRAIN AT FRACTURE.

(BASED ON HEUKELOM)



EXAMPLE

BASE TEMPERATURE OF A GIVEN ASPHALT CEMENT 50°C
SPECIFIED SERVICE TEMPERATURE −28°C
∴ SPECIFIED SERVICE TEMPERATURE IS 78°C BELOW BASE TEMPERATURE
PENETRATION INDEX OF ASPHALT CEMENT −1·0
TIME OF LOADING $10^{4·3}$ SEC (20,000 SEC) (6 HR)
∴ MODULUS OF STIFFNESS OF ASPHALT CEMENT 1,000 KG/CM² = 14,200 LB/IN²

NOTE: 1 KG/CM² = 14·2 LB/IN²

FIG. 42 SUGGESTED MODIFICATION OF HEUKELOM'S AND KLOMP'S VERSION OF VAN DER POEL'S NOMOGRAPH FOR DETERMINING MODULUS OF STIFFNESS OF ASPHALT CEMENTS.

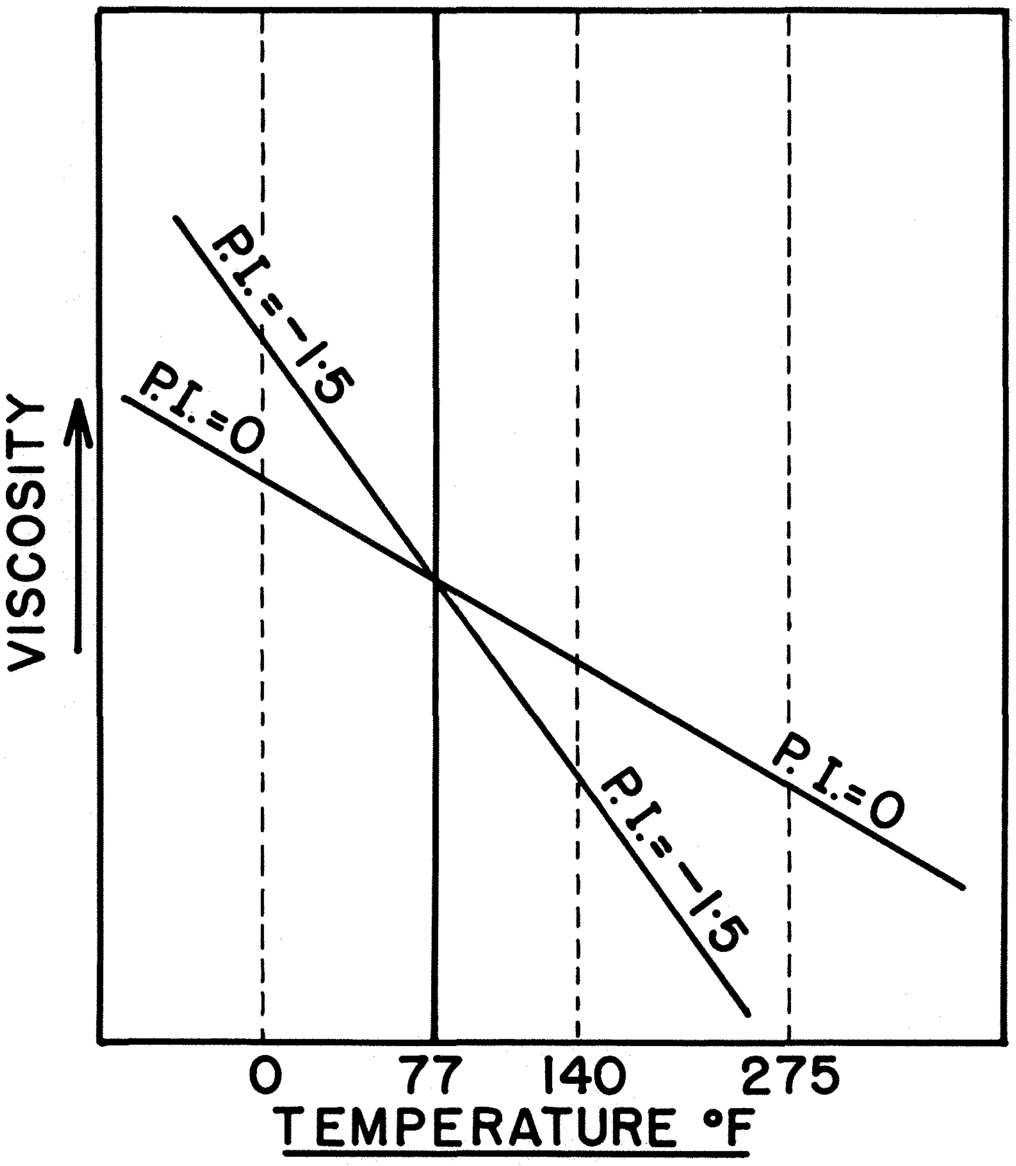
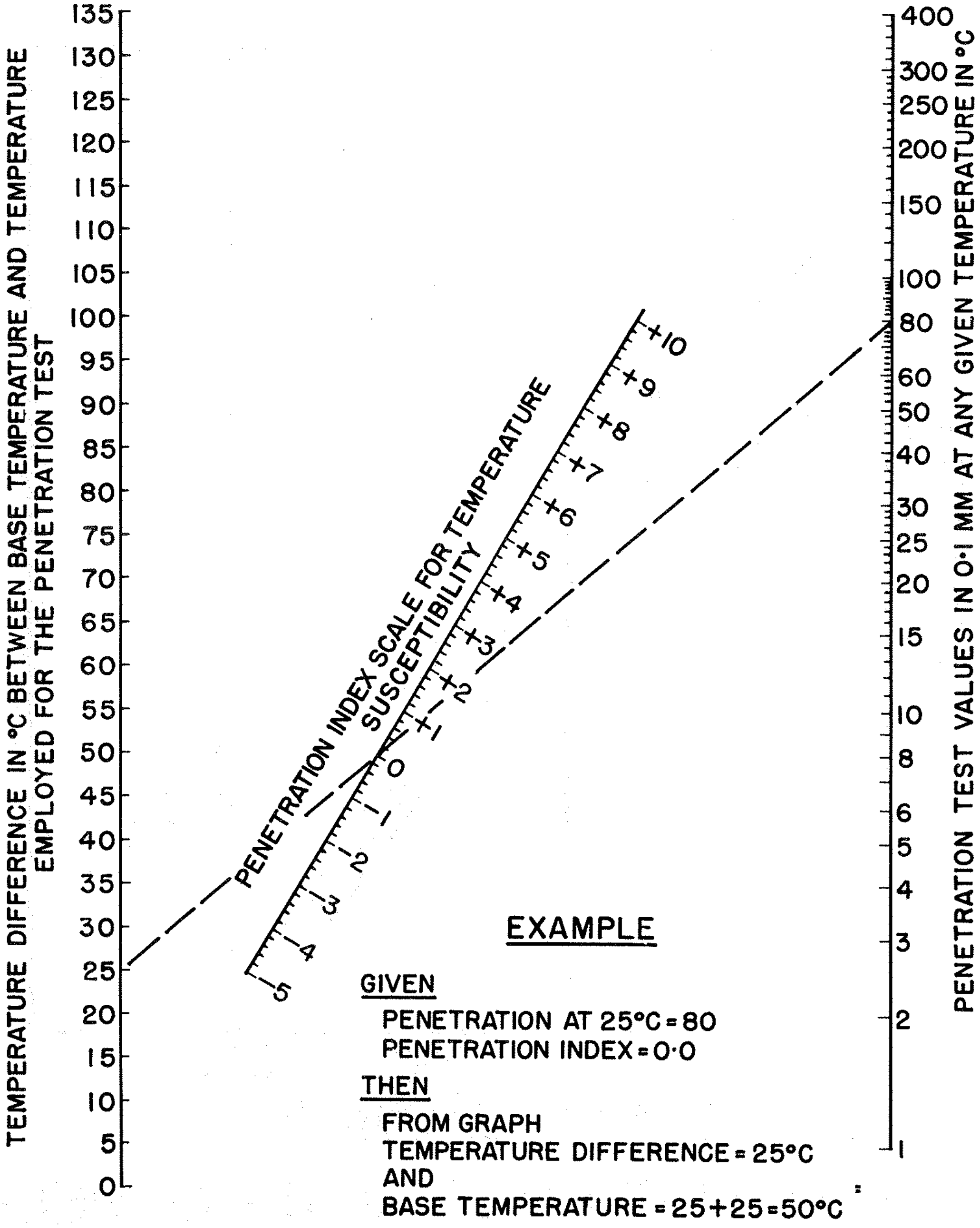


FIG. 43 SKETCH OF GENERAL RELATIONSHIPS BETWEEN VISCOSITY, TEMPERATURE AND PENETRATION INDICES FOR ASPHALT CEMENTS.



EXAMPLE

GIVEN

PENETRATION AT 25°C = 80
PENETRATION INDEX = 0·0

THEN

FROM GRAPH
TEMPERATURE DIFFERENCE = 25°C
AND
BASE TEMPERATURE = 25+25 = 50°C

FIG. 44 SUGGESTED MODIFICATION OF HEUKELOM'S VERSION OF PFEIFFER'S AND VAN DOORMAL'S NOMOGRAPH FOR RELATIONSHIP BETWEEN PENETRATION, PENETRATION INDEX AND BASE TEMPERATURE.

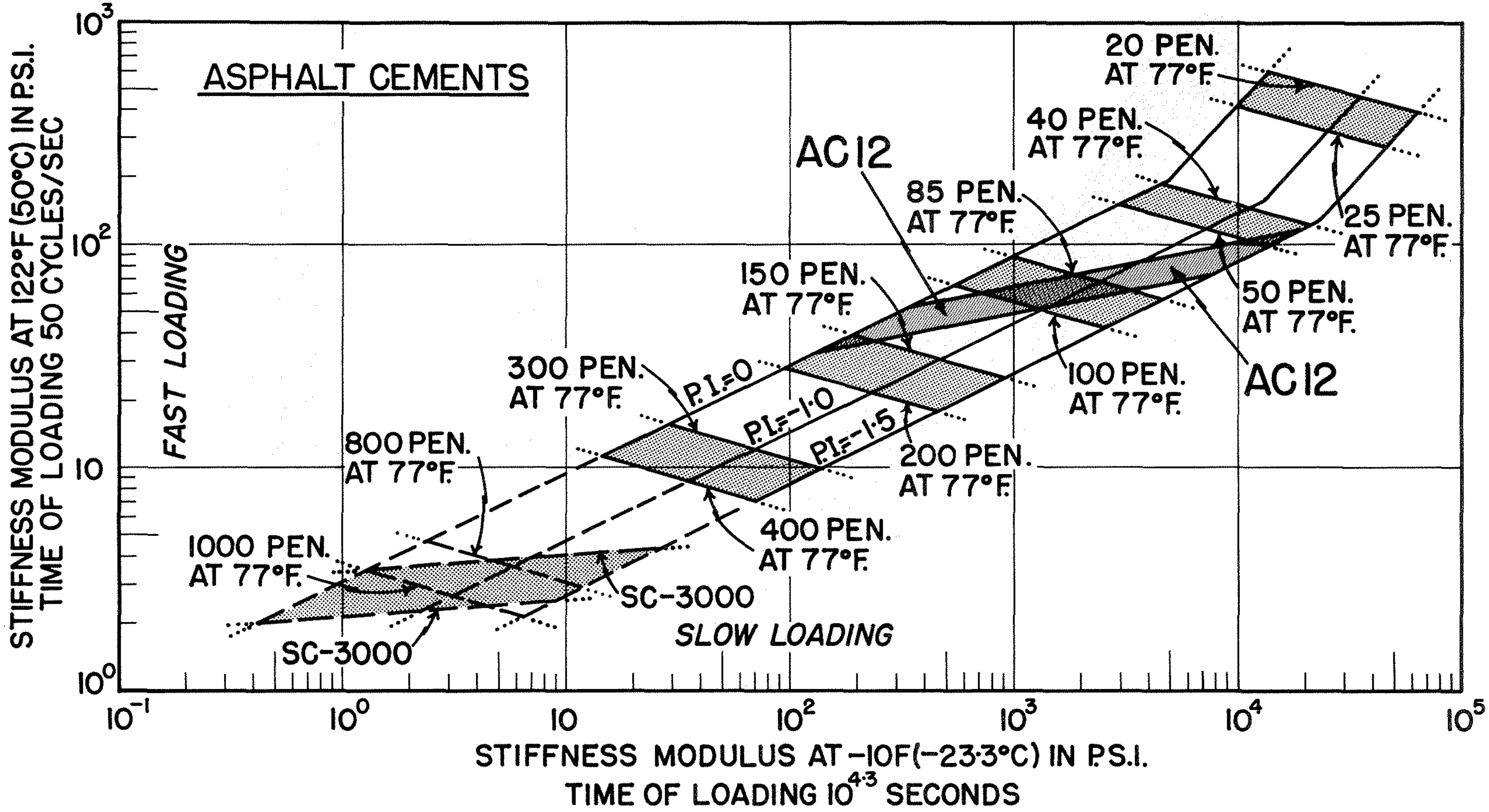


FIG.45 RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT CEMENTS FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (122°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES) AT LOW TEMPERATURE (-10°F).

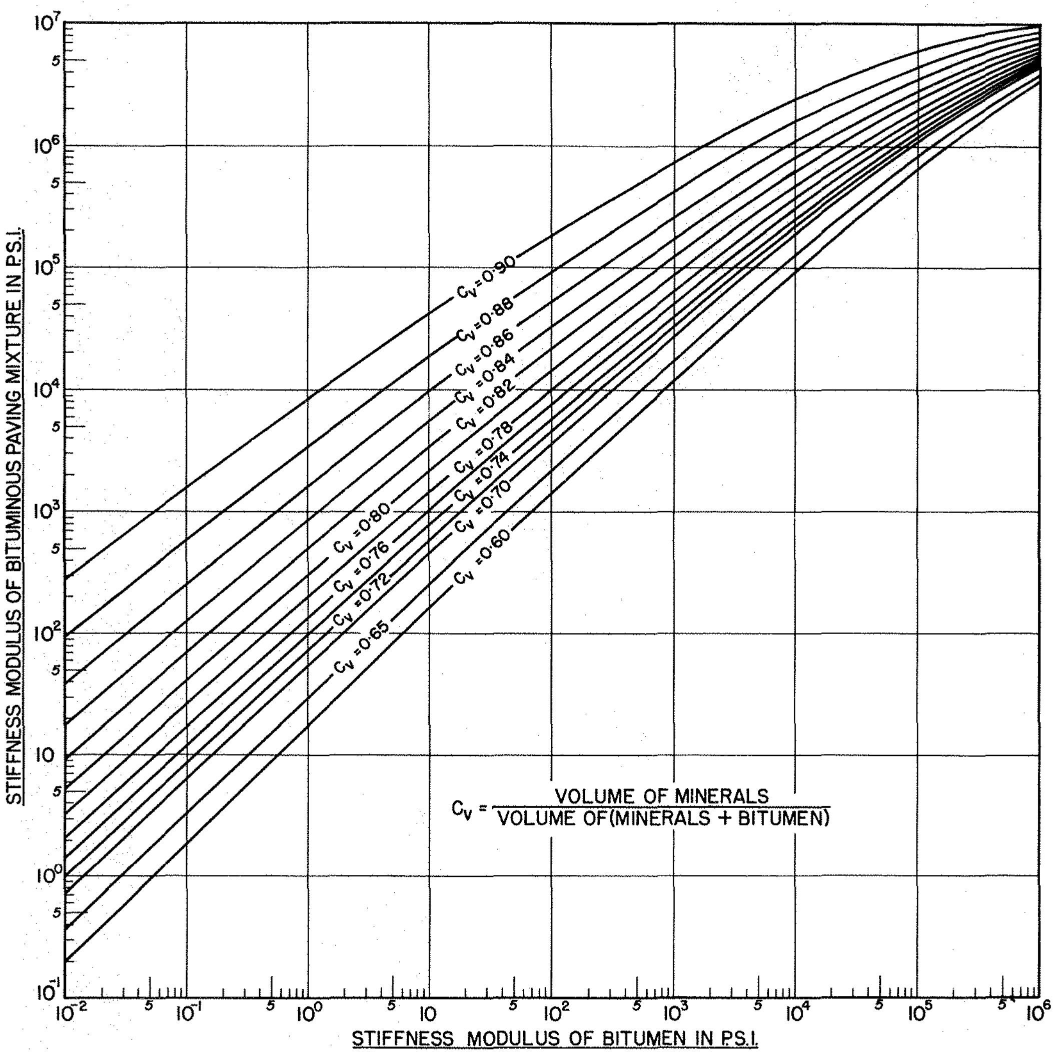


FIG.**46** RELATIONSHIPS BETWEEN MODULI OF STIFFNESS OF ASPHALT CEMENTS AND OF PAVING MIXTURES CONTAINING THE SAME ASPHALT CEMENTS *(BASED ON HEUKELOM AND KLOMP).*

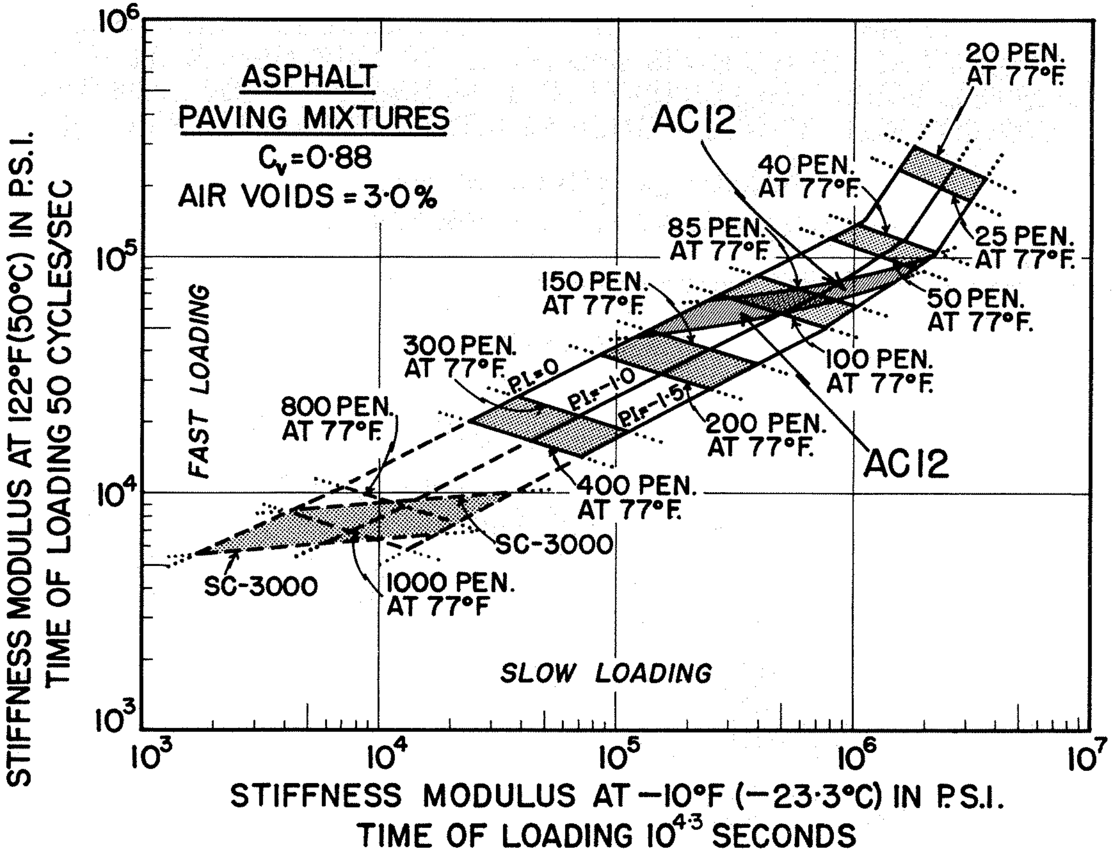


FIG.**47** RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT PAVING MIXTURES FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (122°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES) AT LOW TEMPERATURE (−10°F).

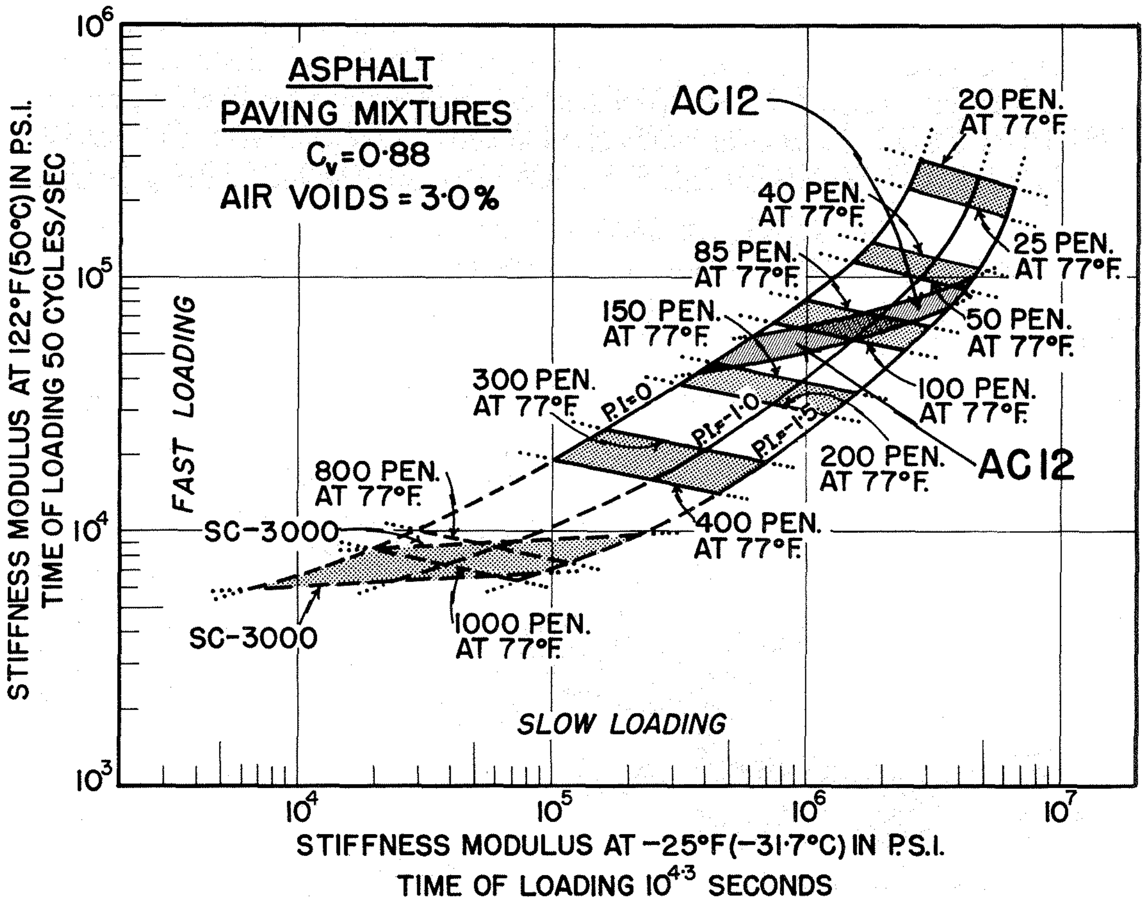


FIG.48 RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT PAVING MIXTURES FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (122°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES) AT LOW TEMPERATURE (−25°F)

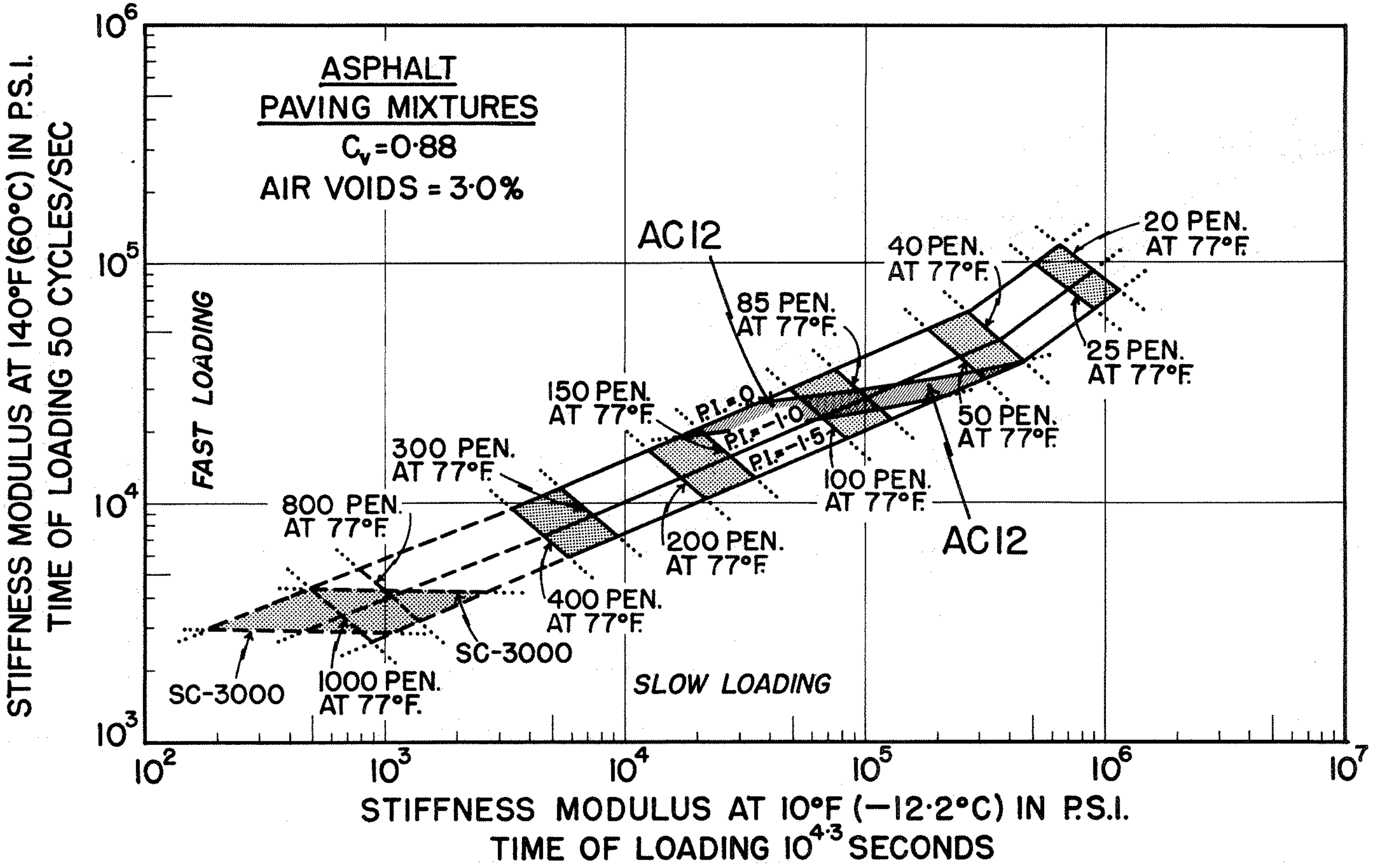


FIG.49 RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT PAVING MIXTURES FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (140°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES AT LOW TEMPERATURE (10°F).

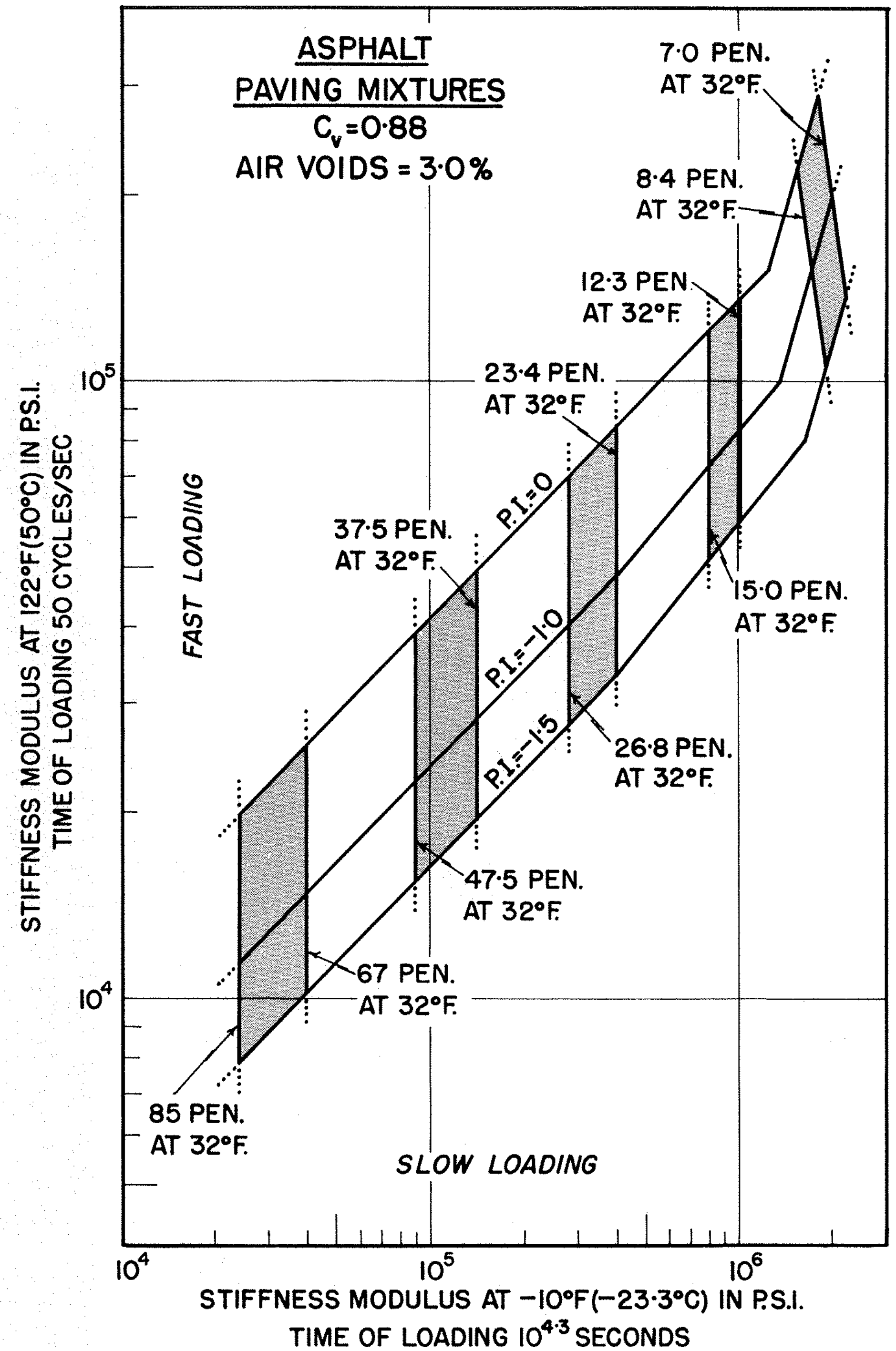


FIG.50 RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT PAVING MIXTURES FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (122°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES) AT LOW TEMPERATURE (−10°F).

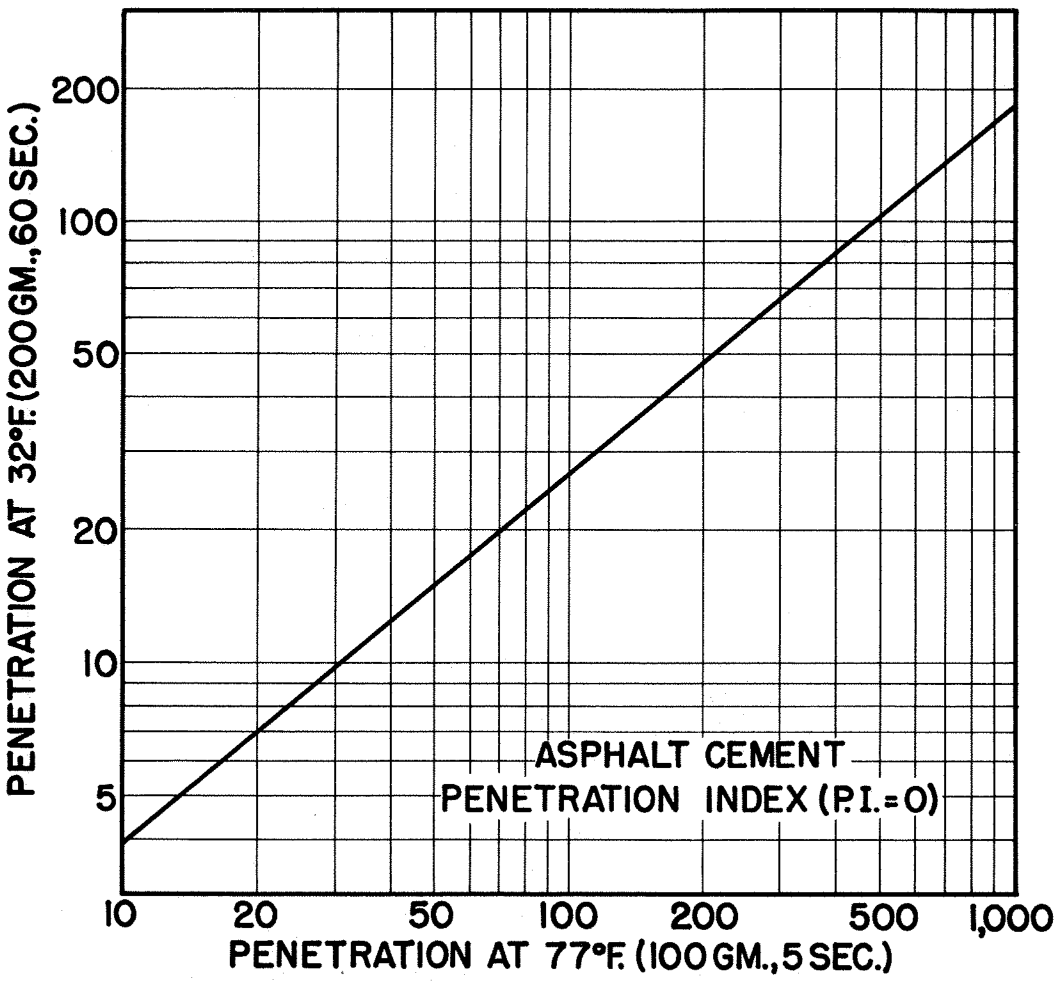


FIG. 51 RELATIONSHIP BETWEEN PENETRATION AT 77°F. AND PENETRATION AT 32°F. FOR AN ASPHALT CEMENT WITH A P.I. OF 0.

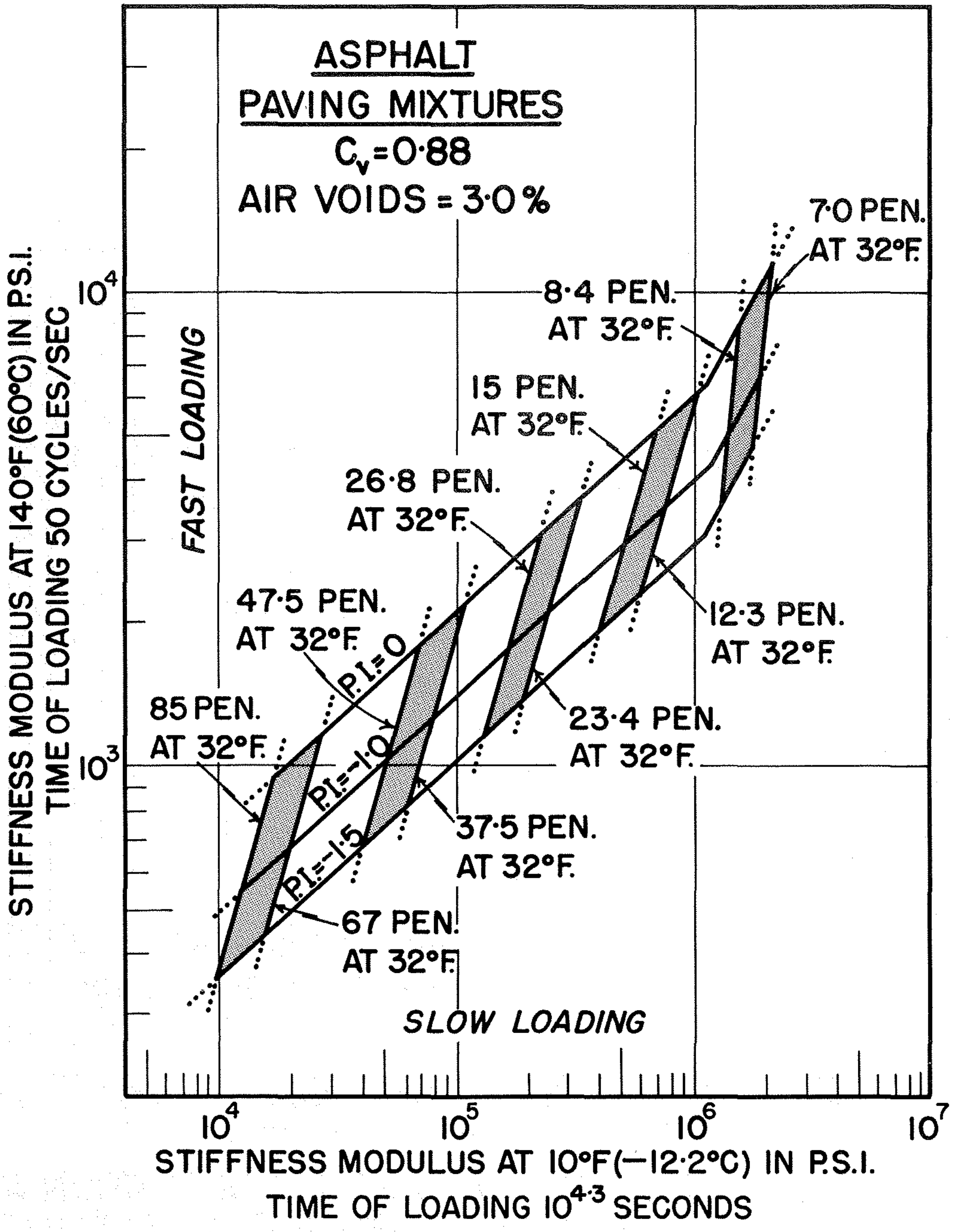


FIG.52 RELATIONSHIP BETWEEN STIFFNESS MODULI FOR ASPHALT PAVING MIXTURES FOR HIGH RATE OF LOADING (HIGH SPEED TRAFFIC) AT HIGH TEMPERATURE (140°F) VERSUS SLOW SPEED OF LOADING (TEMPERATURE STRESSES) AT LOW TEMPERATURE (10°F).

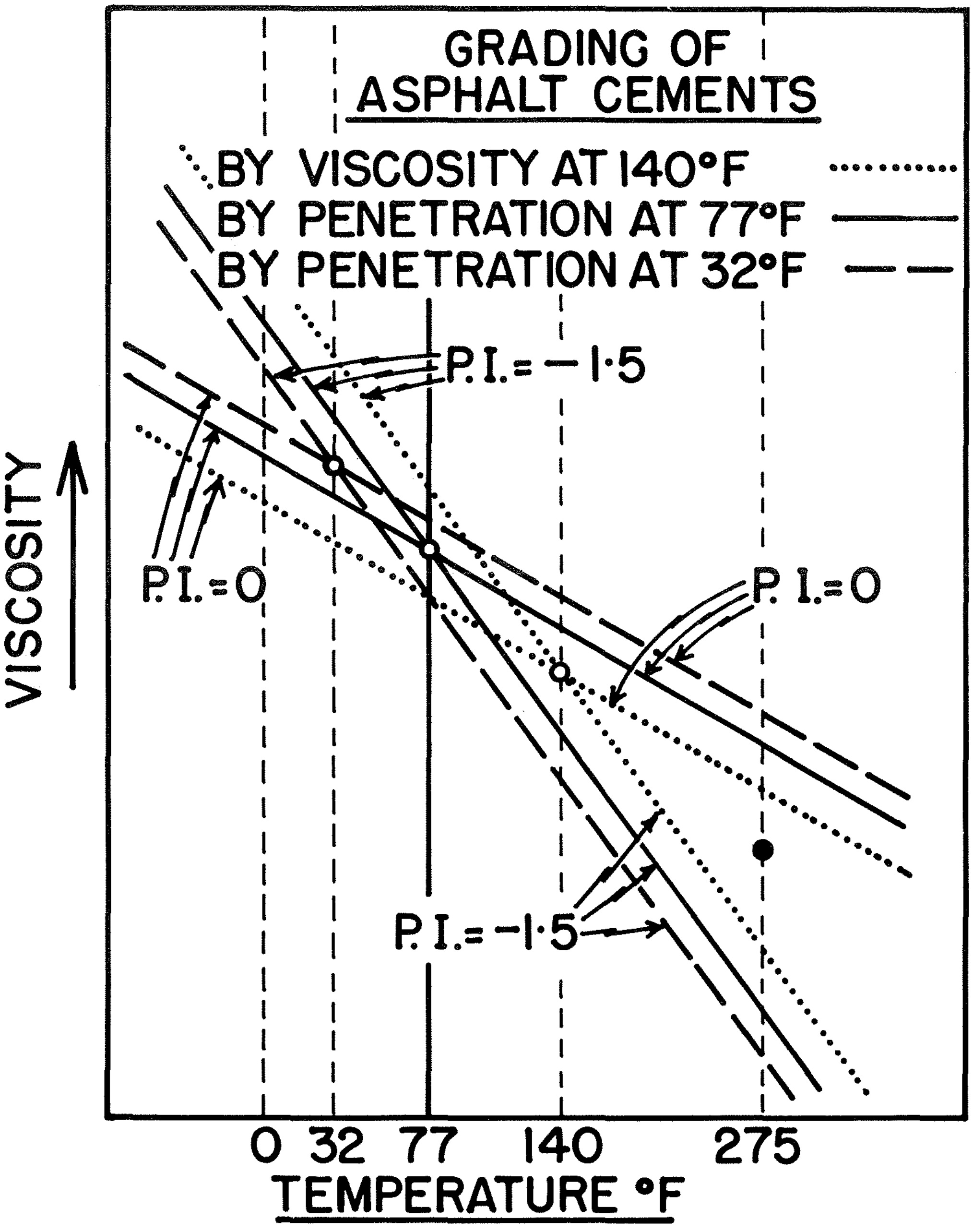


FIG. **53** SKETCH ILLUSTRATING CONSEQUENCES OF GRADING ASPHALT CEMENTS BY VISCOSITY AT 140°F, BY PENETRATION AT 77°F AND BY PENETRATION AT 32°F.