JOINT HIGHWAY RESEARCH PROGRAM
PROJECT 72-03-3
EVALUATION OF BITUMINOUS MIXES IN PAVEMENT STRUCTURES
INTERIM REPORT III

SCHOOL OF
CIVIL ENGINEERING
OKLAHOMA STATE UNIVERSITY

A PRELIMINARY STUDY OF THE USE OF THE STIFFNESS CONCEPT IN MINIMIZING LOW-TEMPERATURE TRANSVERSE CRACKING

by

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Phillip G. Manke

**RESEARCH
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CHAPTER I

INTRODUCTION

Transverse cracking in flexible highway pavements is considered to be a serious and extensive problem by the asphalt paving technologist. There is wide agreement that these cracks are caused primarily by the thermal contraction of the pavement structure at low temperatures and appear in the surface when the asphalt concrete pavement has been unable to absorb the strains generated by the thermal contraction forces. This cracking of the asphalt concrete is related to the rheological properties of the bitumen, and it appears necessary that a state highway department be able to specify bitumens which can accomodate the thermal strains imposed by the various environmental conditions encountered. To accomplish this, numerous investigations have been directed towards characterizing the rheological and consistency properties of the bitumens at low temperatures. These studies indicated that the most satisfactory parameter to characterize the low-temperature response of binders and mixtures is the "stiffness modulus". The use of a limiting stiffness value, or what is called a "critical" stiffness value, seems to be a very useful quantitative guide in selecting asphalt cements that will enable low-temperature transverse pavement cracking to be avoided during a pavement's service life.

This report, reviews the literature related to the different direct and indirect methods of determining the stiffness modulus of asphalt binders and/or mixtures. The concept of limiting stiffness in selecting asphalt binders was extensively reviewed and the main findings are included.

To investigate the behavior and response of Oklahoma asphalt binders and mixtures at low temperature, the stiffness moduli of thirty-one (31) asphalt cement samples secured from various sources in Oklahoma were determined. The study also included determining the stiffness moduli of different penetration grades of asphalt binders (blended at the OSU Asphalt Lab) and mixtures prepared in accordance with OHD - Type C surface mix specifications. The test results were compared to the findings of other investigations.

CHAPTER II

LITERATURE REVIEW

Introduction

Extensive field inventories and test sections constructed in the late 1950's and early 1960's, primarily in Canada and the northern United States, indicated that the asphaltic component of the pavement was a major variable in affecting low-temperature shrinkage cracking. There is now a widespread agreement that the most satisfactory parameter to characterize the low-temperature response of asphalts and mixes is the "stiffness modulus".

Definition

The concept of stiffness was first introduced by Van der Poel (18) as follows:

$$S(t, T) = \left[\frac{\sigma}{\varepsilon}\right]_{t,\ T}$$

Where $S(t, T)$ = Stiffness modulus, usually in terms of psi or kg/cm^2, of the material for a particular time of loading, t, and for a particular temperature, T,

σ = Stress, at t and T, and

ε = Unit strain, at t and T.

This modulus is an extension of Young's Modulus of elasticity for a purely elastic solid, but specifies the time and temperature, thereby recognizing the viscoelastic nature of the material. In addition, Van der Poel showed that the hardness and rheological type of the bitumens were influential on the magnitude of stiffness modulus for any particular time and temperature.

Methods of Determining Stiffness Modulus

The methods used to determine the stiffness of a bituminous material can be classified as follows:

A. Models - Mathematical expressions describing the behavior of different combinations of springs and dashpots can be written, and it is assumed that these expressions describe the behavior of the viscoelastic material. These expressions are sometimes very complicated, and engineers have often found that these models, even the simple ones, do not adequately represent the actual behavior of asphalt cement.

B. Direct Measurements or Testing - These include creep, relaxation, or constant-rate-of-strain testing in either tension or compression, or by dynamic or flexural testing methods.

C. Indirect Estimation - There are many different ways to measure stiffness indirectly, either by the original Van der Poel method, or by the modification of this method as suggested by Heukelom (9) or McLeod (13). These indirect methods are so termed because they provide an estimate of stiffness based on direct laboratory measurements. Routine test data is transformed into stiffness values using nomographs and/or charts.

Individual Approaches to Indirect Estimate of Stiffness Modulus

Van der Poel Theory

Van der Poel presented the original method of determining stiffness of a bitumen in 1954, in the form of a nomograph derived from experimental data from two types of tests:

1. a constant-stress test (static creep test in tension), and
2. a dynamic test with an alternating stress of constant amplitude and frequency.

Two routine tests of the bitumen are required to determine its stiffness modulus (S) from the nomograph. These tests are the penetration test (ASTM Designation D5) and the softening point test (ASTM Designation D36). From the penetration value and softening point temperature, the penetration index (P.I.) for the asphalt can be calculated. It is related to the slope of the line obtained by plotting the logarithms of the penetration of the bitumen against temperature (Fig. 1). The assumption is that the penetration (100 gm, 5 sec.) at the temperature of the ring-and-ball softening point, $T_{R\&B}$, is approximately 800. From Fig. 1, Pfeiffer and Van Doormall expressed the tangent of θ in terms of P.I.

$$\tan\theta = \frac{\log 800 - \log P}{T_{R\&B} - T} = \frac{20 - P.I.}{10 + P.I.}$$

where

P = penetration in 0.1mm at a temperature T in ^{o}C

$T_{R\&B}$ = softening temperature as determined by the "Ring and Ball" Softening Point Test

Using this relationship, the Pfeiffer and Van Doormaal Penetration Index can be calculated as follows:

$$P.I. = \frac{20 - 500 \tan \Theta}{1 + 50 \tan \Theta}$$

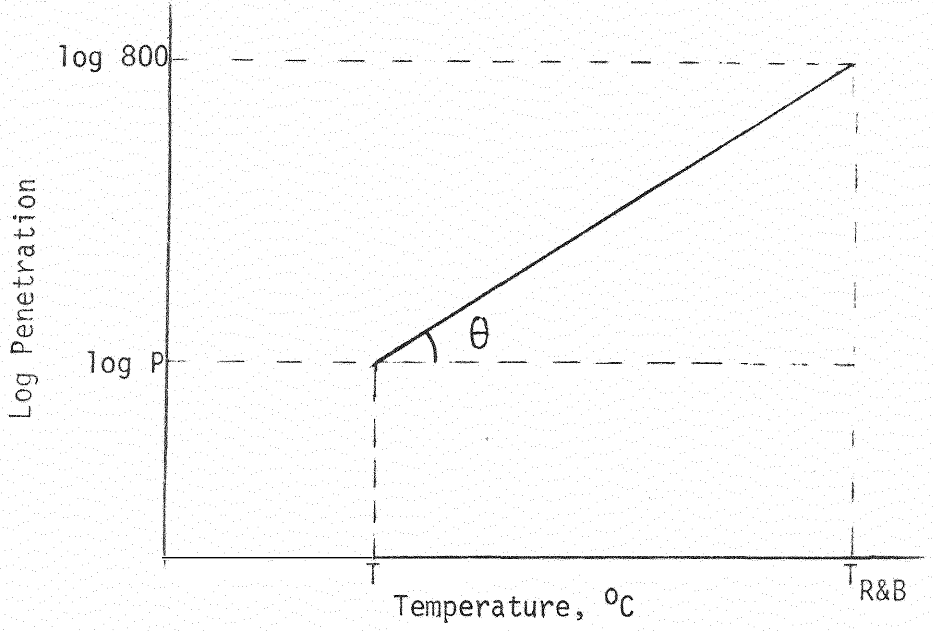


Figure 1. Penetration Index as Defined by Pfeiffer and Van Doormaal

This penetration index can also be determined by a nomograph introduced by Pfeiffer and Van Doormal (15) to indicate the temperature susceptibility of the penetration of the asphalt (Fig. 2). In general, the penetration index of most asphalts varies from -2.6 to +8.0 (18). The lower the P.I., the higher the temperature susceptibility.

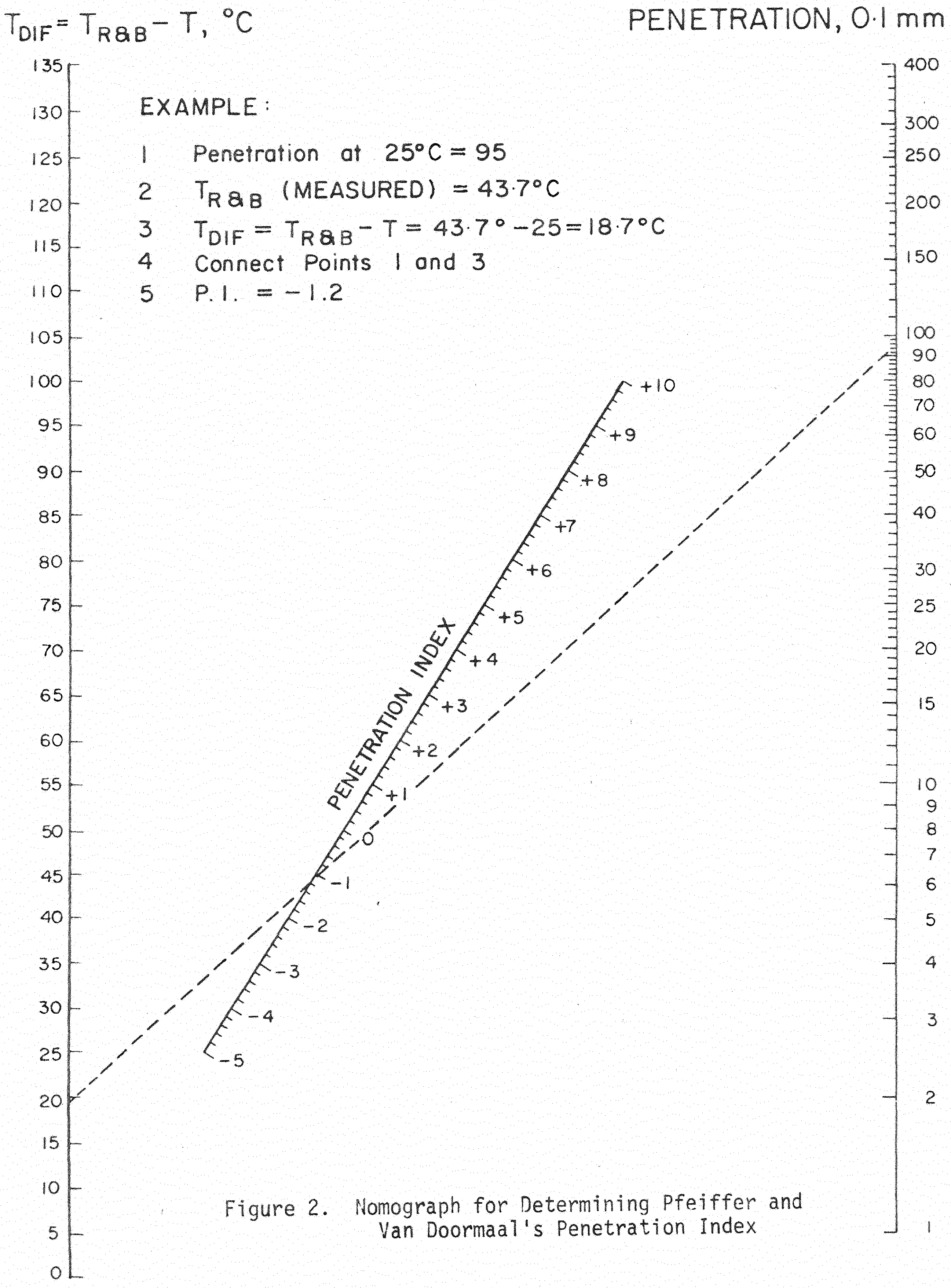
The use of Van der Poel's nomograph to estimate asphalt stiffness can be summarized in the following steps:

1. Measure penetration at 77°F, 100 gm, 5 sec.,
2. Measure softening point, $T_{R\&B}$,
3. Calculate Penetration Index, P.I., according to Pfeiffer and Van Doormal, using Fig. 1 or Fig. 2,
4. Estimate stiffness, using the nomograph (Fig. 3), from the folowing three parameters:
    a. time of loading,
    b. softening-point temperature minus test temperature, and
    c. penetration index of the asphalt.

Van der Poel (18) checked the accuracy of his nomograph and concluded that the variation in measured stiffness values of an asphalt and the stiffness obtained from the nomograph seldom exceeded a factor of 2.

Heukelom Modification for Bitumens and Bituminous Mixtures

It has been reported in the literature that for a number of North American asphalts (blown asphalts and asphalts having considerable wax contents), the Van der Poel method of estimating the stiffness of these asphalts could result in some significant errors (1). As a result, Heukelom developed a Bitumen Test Data Chart (10) to relate the consistency of bitumens with temperature (Fig. 4). The advantage of this chart is that it allows a "corrected" softening point to be determined for a waxy



EXAMPLE:

1 Penetration at 25°C = 95

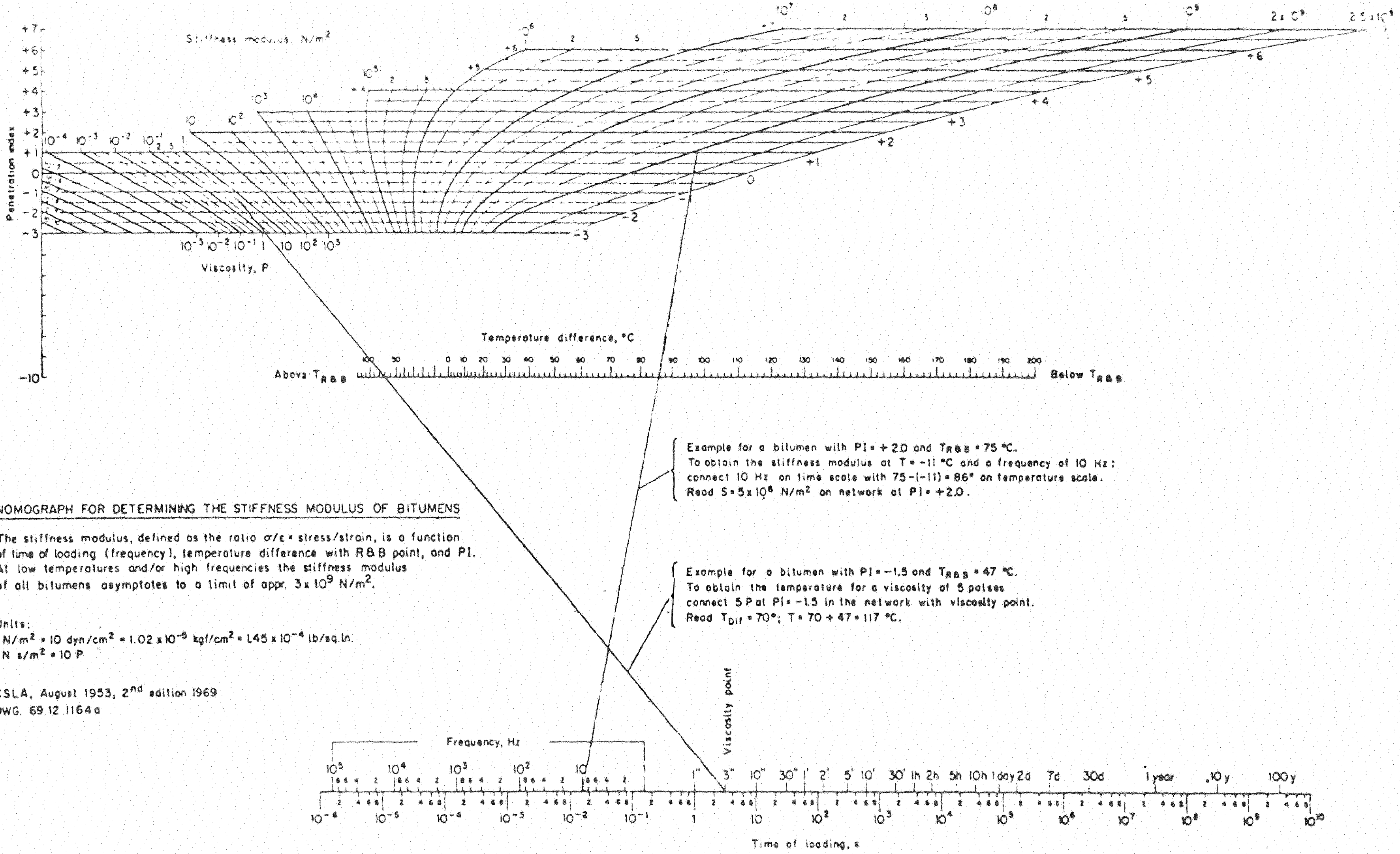
2 $T_{R\&B}$ (MEASURED) = 43·7°C

3 $T_{DIF} = T_{R\&B} - T = 43{\cdot}7° - 25 = 18{\cdot}7°C$

4 Connect Points 1 and 3

5 P. I. = − 1.2

Figure 2. Nomograph for Determining Pfeiffer and Van Doormaal's Penetration Index



NOMOGRAPH FOR DETERMINING THE STIFFNESS MODULUS OF BITUMENS

The stiffness modulus, defined as the ratio σ/ε = stress/strain, is a function of time of loading (frequency), temperature difference with R&B point, and PI. At low temperatures and/or high frequencies the stiffness modulus of all bitumens asymptotes to a limit of appr. 3×10^9 N/m².

Units:
1 N/m² = 10 dyn/cm² = 1.02 x 10⁻⁵ kgf/cm² = 1.45 x 10⁻⁴ lb/sq.in.
1 N s/m² = 10 P

KSLA, August 1953, 2nd edition 1969
DWG. 69.12.1164a

Example for a bitumen with PI = +2.0 and $T_{R\&B}$ = 75 °C.
To obtain the stiffness modulus at T = -11 °C and a frequency of 10 Hz:
connect 10 Hz on time scale with 75-(-11) = 86° on temperature scale.
Read $S = 5 \times 10^8$ N/m² on network at PI = +2.0.

Example for a bitumen with PI = -1.5 and $T_{R\&B}$ = 47 °C.
To obtain the temperature for a viscosity of 5 poises
connect 5 P at PI = -1.5 in the network with viscosity point.
Read T_{Dif} = 70°; T = 70 + 47 = 117 °C.

Figure 3. Van Der Poel's Nomogram for determining stiffness modulus of Bitumens

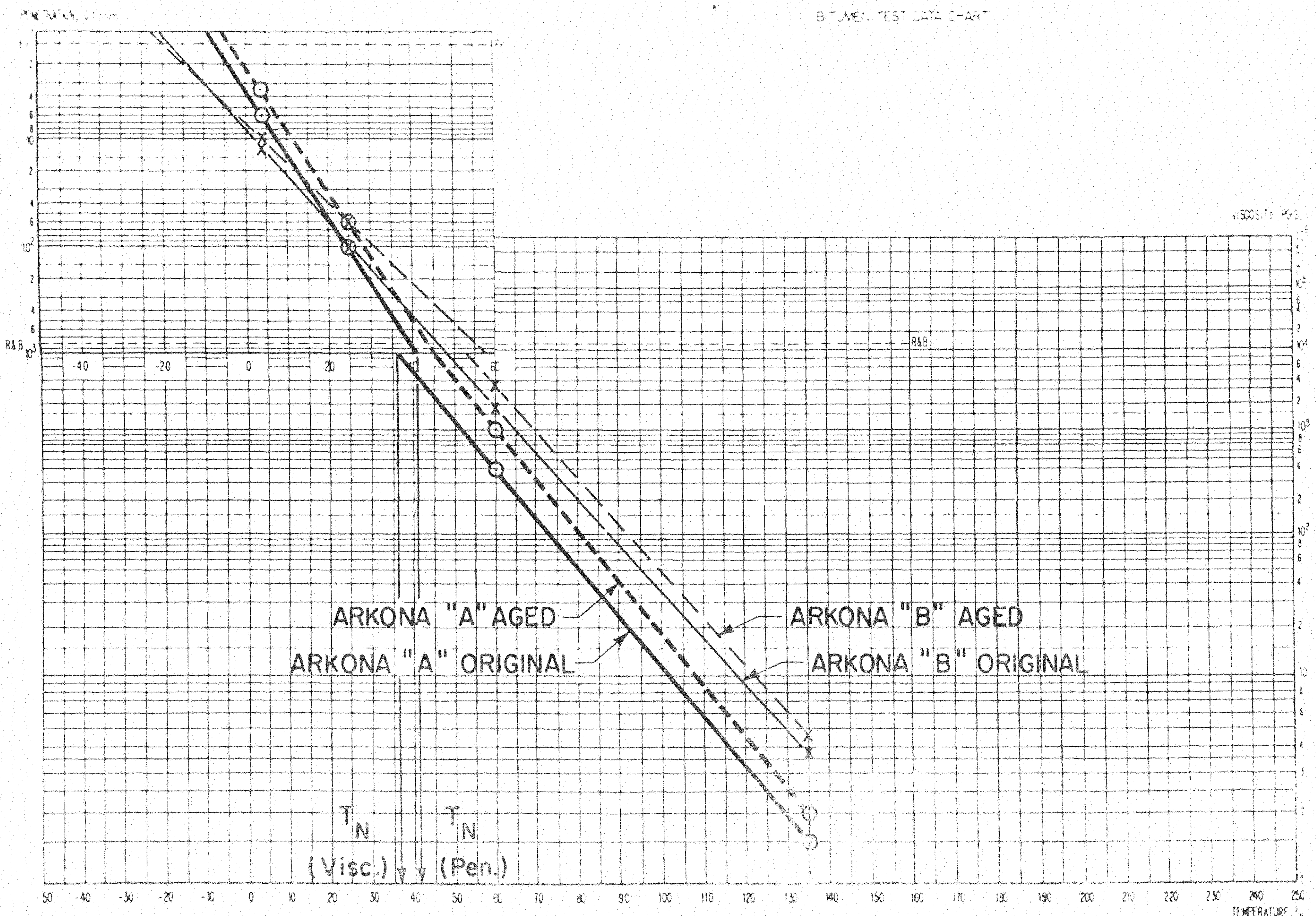


Figure 4. Heukelom's Bitumen Test Data Chart

or blown asphalt. Heukelom suggested a modification of the Van der Poel method for estimating the stiffness modulus of asphalt cements at low temperatures. His modification can be summarized as follows:

1. Plot the viscosity and penetration values on the "Bitumen Test Data Chart",

2. A "corrected" Ring-and-Ball softening point, T_N, can be found by extending the penetration branch downward. This T_N replaces $T_{R\&B}$.

3. The Pfeiffer and Van Doormall P.I. is then replaced by 0, which can be calculated as follows:

$$0 = 20 \cdot \frac{T_{2p} - T_N - 111}{T_{2p} - T_N + 222}$$

Where T_{2p} = temperature at which the viscosity is equal to 2 poises. This temperature can be determined from the Bitumen Test Data Chart.

T_N = corrected softening point.

4. Use the Van der Poel nomograph to estimate the stiffness modulus for the particular time of loading and temperature. It should be noted that Heukelom suggested a slightly modified Van der Poel's nomograph (9) in his earlier work; however, in a more recent paper, he recommended the use of the original nomograph when the "corrected" softening point, T_N, is used (8, 10).

Stiffness Modulus of Bituminous Mixtures

Based on the stiffness modulus of the asphalt cement, it is possible to determine the stiffness of an asphalt concrete mixture from the following ralationship, which was first developed by Van der Poel (17) and later modified by Heukelom and Klomp (8):

$$S_{mix} = S_{ac}\left[1.0 + \left(\frac{2.5}{n}\right)\left(\frac{C_v}{1.0 - C_v}\right)\right]^n$$

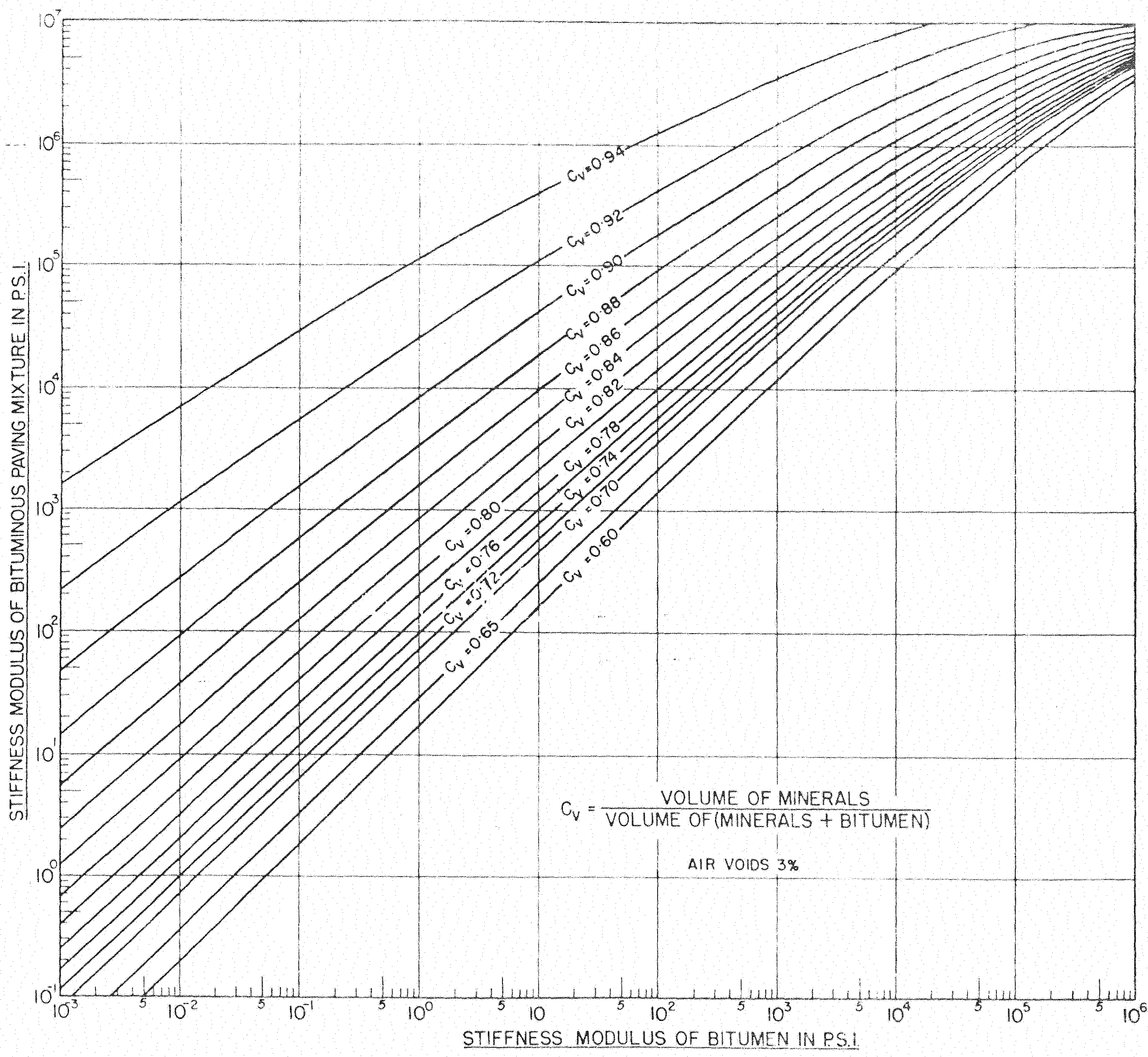


Figure 5. Relationships Between Moduli of Stiffness of Asphalt Cements and of Paving Mixtures Containing the Same Asphalt Cements (after Heukelom and Klomp)

where

$$n = 0.83 \log_{10} \frac{4 \times 10^5}{S_{ac}} ,$$

S_{mix} = stiffness of asphalt concrete mixture, in kg/cm^2,

S_{ac} = stiffness of asphalt cement, in kg/cm^2, and

C_v = volume concentration of the aggregate in the mixture, defined as follows:

$$\frac{\text{Volume of Compacted aggregate}}{\text{Volume of (asphalt + aggregate)}} = \frac{100 - \%\ \text{VMA}}{100 - \%\ \text{Air Voids}}$$

When dealing with asphalt concrete cores cut from a pavement or a compacted laboratory sample, the previous equation for C_v can be replaced by an equivalent equation as follows:

$$C_v = \frac{1}{1 + C}$$

where

$$C = \frac{W_s}{W_g} \cdot \frac{G_g}{G_s} = \frac{\%\ \text{of asphalt by weight of aggregate}}{100.0} \left[\frac{G_g}{G_s} \right]$$

W_s = weight of asphalt,

W_g = weight of aggregate,

G_s = specific gravity of asphalt, and

G_g = specific gravity of aggregate.

A chart for solving the equation of S_{mix}, for a range of C_v values from 0.6 to 0.94, is presented in Fig. 5 (8). Heukelom and Klomp stated that the relation of S_{mix} is applicable to well-compacted mixtures with about 3 percent air voids and C_v values between about 0.7 and 0.9. For mixtures with air voids greater than 3.0 percent, Draat and Soômer (19) derived a correction to be applied to the C_v value. The corrected C_v value (C'_v) is determined as follows:

$$C'_v = \frac{C_v}{1 + H}$$

Where

H = actual air voids - 3.0%

McLeod's Method for Bitumen and Bituminous Mixtures

In this method, McLeod (13) presented an alternate way of showing the temperature susceptibility of an asphalt. His method is based on the relationship between viscosity at 275°F (or at 140°F) and penetration at 77°F. McLeod believed that this method provided a very reasonable basis for expressing differences in temperature susceptibility, and he demonstrated that for the asphalt cements of the same penetration at 77°F, there were differences in their viscosities at 275°F. As this approach for evaluating asphalt temperature susceptibility is different from that employed for determining penetration index, the term "Penetration-Viscosity Number" (PVN) was used instead of penetration index (P.I.).

McLeod"s method for estimating stiffness modulus of bitumens may be summarized as follows:

1. The penetration-vixcosity number or PVN is to be estimated from Fig. 6. Lines for PVN = 0 and PVN = -1.5 were determined experimentally by plotting a large number of asphalt test results. Other PVN's can be established by interpolation or extrapolation by means of the following equation:

$$PVN = \frac{\text{Log } L - \text{Log } X}{\text{Log } L - \text{Log } M} (-1.5)$$

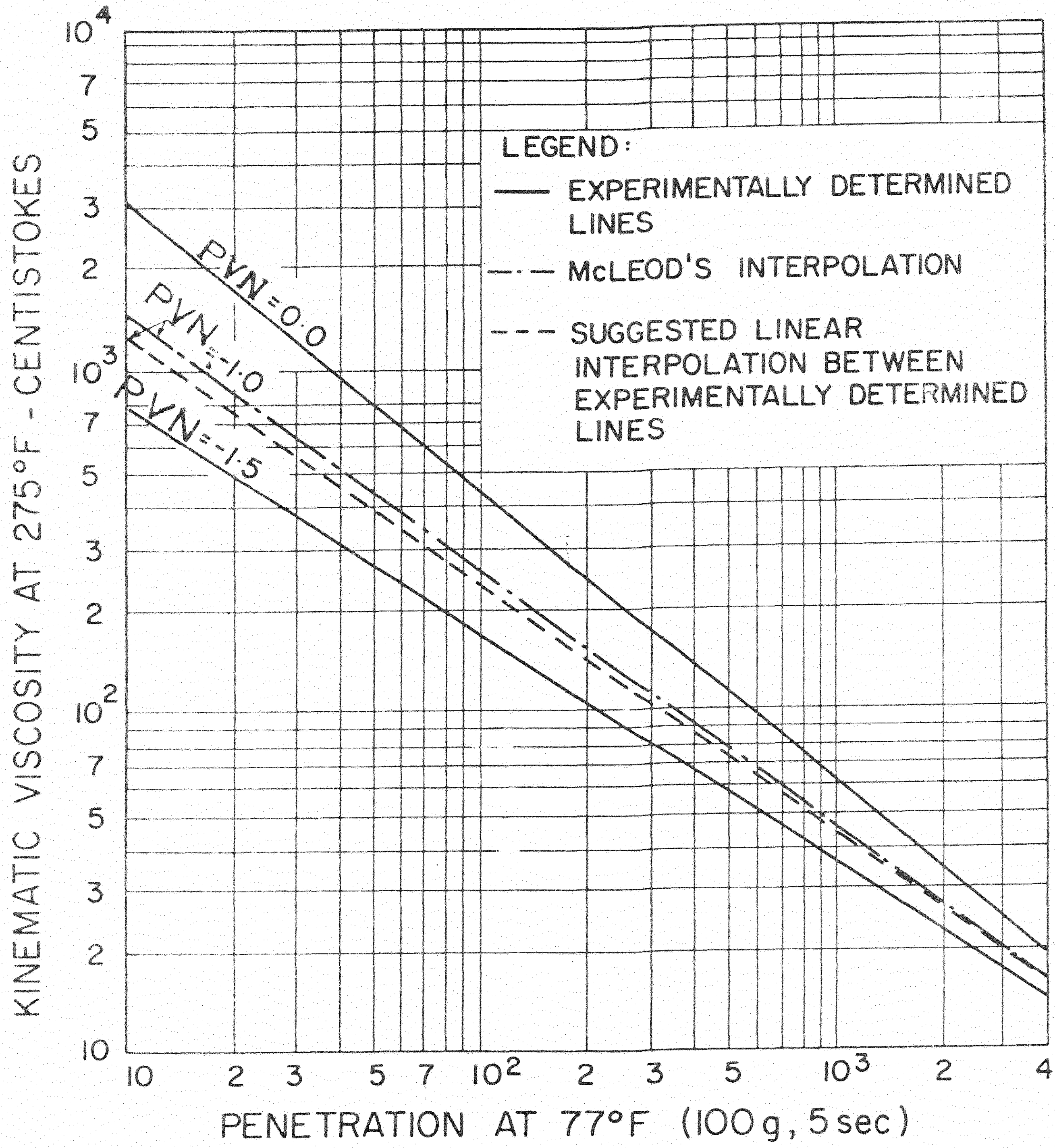


Figure 6. McLeod's Chart for estimating the "PVN" of an Asphalt Cement

Where X = viscosity in centistokes at 275^{O}F for the asphalt cement for which PVN is to be determined,

L = viscosity in centistokes at 275^{O}F for a PVN of 0.0, determined from Fig. 6 for the penetration at 77^{O}F of the given asphalt cement.

M = viscosity in centistokes at 275^{O}F for PVN of -1.5, determined from Fig. 6 for the penetration at 77^{O}F of the given asphalt cement.

2. The ring-and ball softening point temperature ($T_{R\&B}$) is called the "base temperature" by McLeod and this value is determined from the nomograph in Fig. 7 rather than by actual test. Fig. 7 is the same nomograph presented by Pfeiffer and Van Doormaal (see Fig. 2). In using this figure, McLeod substituted his PVN's in place of the "Penetration Index" values.

3. Modulus of stiffness of the asphalt is then determined using McLeod's modification of Heukelom's and Klomp's nomograph as shown in Fig. 8.

To estimate the stiffness modulus of asphaltic mixtures, McLeod used Heukelom's method, as discussed previously. However, because the estimated stiffness modulus of the asphalt cement itself may differ by the two methods, the values for the mix would similarly differ.

Comparison of Stiffness Modulus Determined by Different Indirect Methods

To show the magnitude of the differences in results obtained from the previous methods, Haas (6) presented the following table (TableI) for an asphalt cement from the St. Anne Test Road (20).

Although, Haas chose a somewhat extreme situation for the comparison, it is readily apparent that very considerable differences can occur

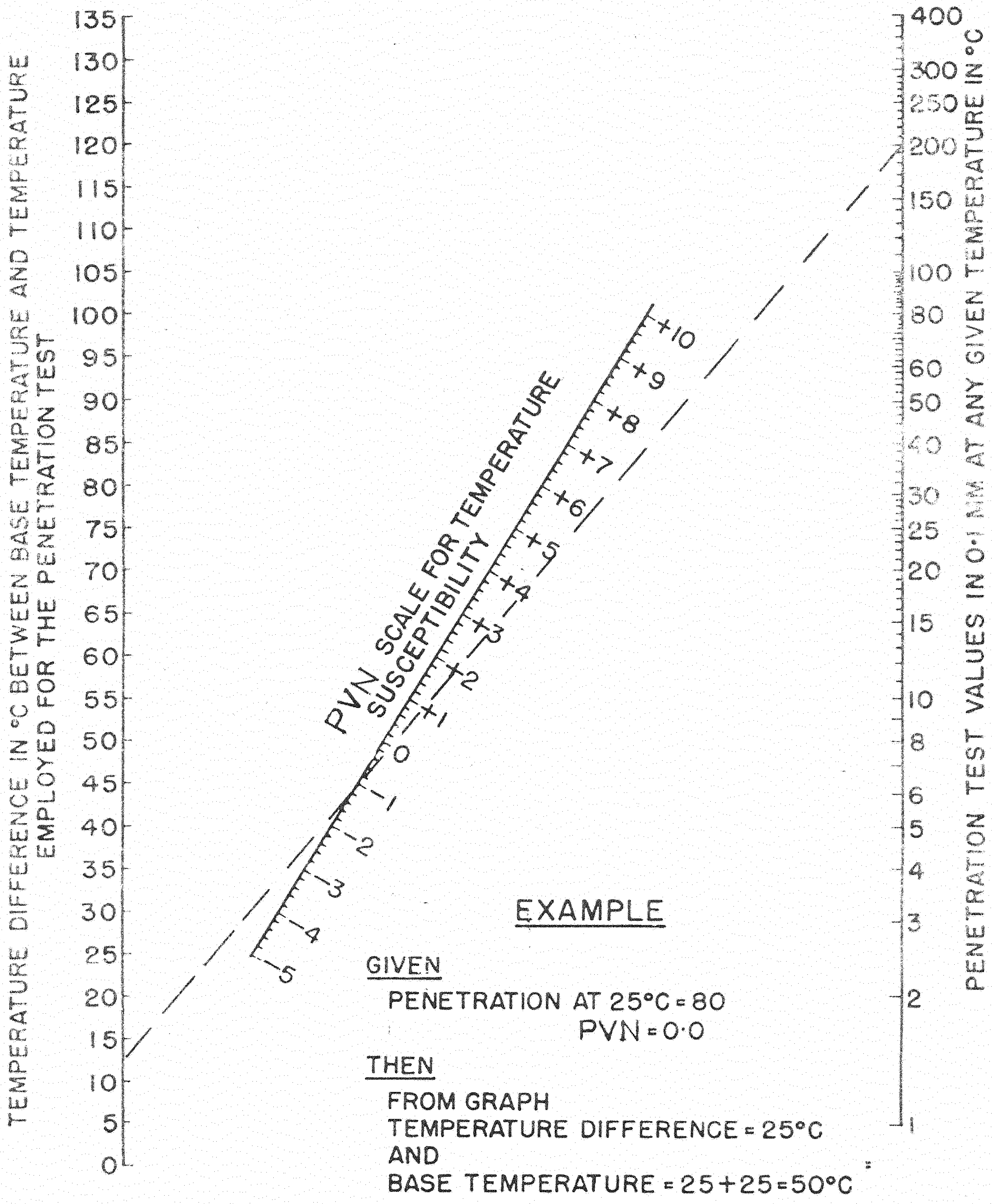
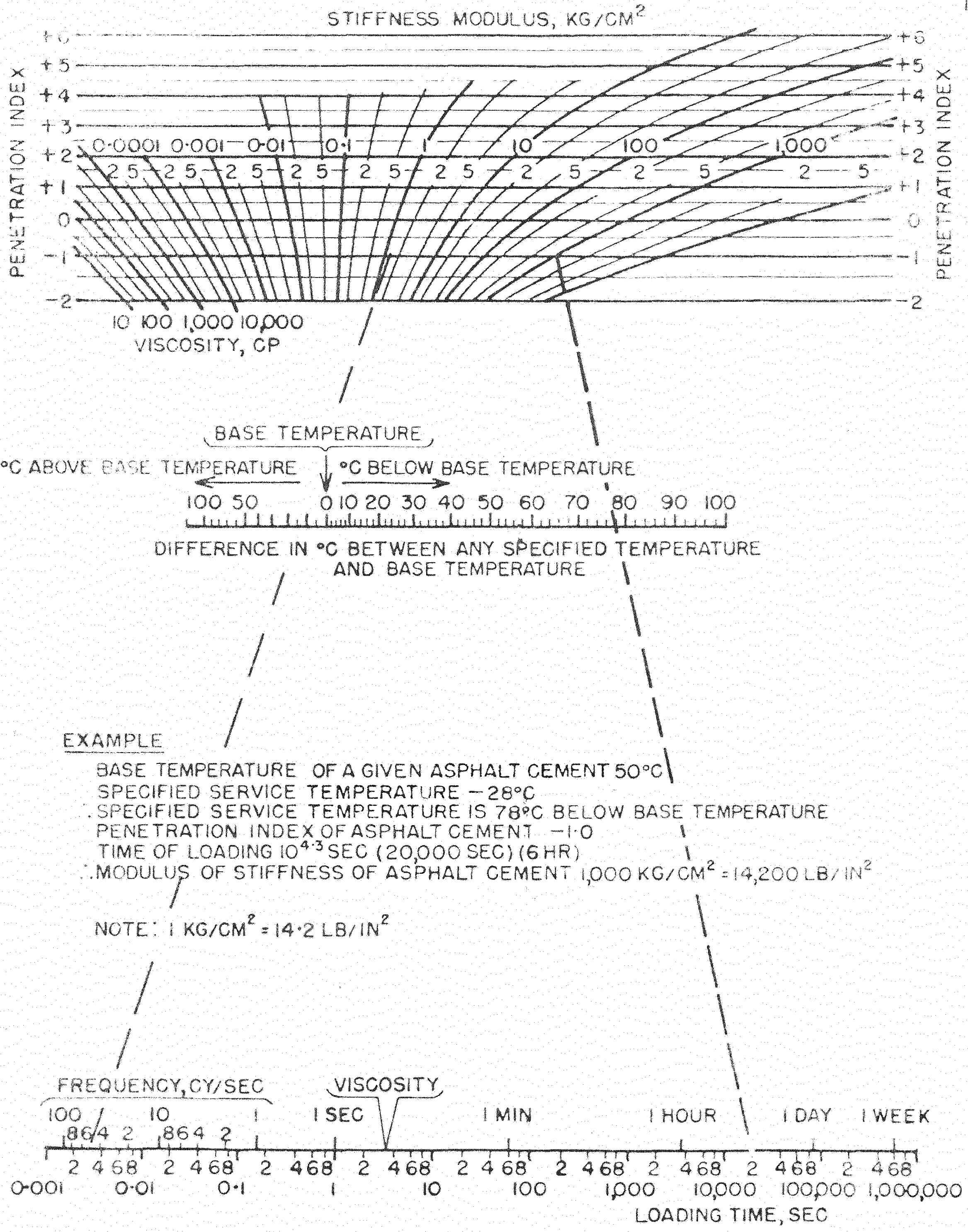


Figure 7. Suggested Modification of Heukelom's Version of Pfeiffer's and Van Doormal's Nomograph for Relationship Between Penetration, Penetration Viscosity Number and Base Temperature.



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 $10^{4 \cdot 3}$ 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

Figure 8. Suggested Modification of Heukelom's and Klomp's Version of Van Der Poel's Nomograph for Determining Modulus of Stiffness of Asphalt Cements.

TABLE I

COMPARISON OF VARIOUS METHODS FOR INDIRECTLY ESTIMATING THE STIFFNESS MODULUS OF AN ASPHALT CEMENT (AFTER ANDERSON AND HAAS)

Characteristic	Original Low-Viscosity-Asphalt Cement From St. Anne Test Road
1. Penetration, 77°F, 100 gm, 5 sec	192
2. Viscosity at 275°F, c St	110
3. Softening Point (Measured) $T_{R\&B}$	119°F (48°C)
4. "Corrected" $T_{R\&B}$ (Fig. 4)	95°F (35°C)
5. Pfeiffer and Van Doormaal P.I. (Fig. 1 or Fig. 2)	+2.9
6. "Corrected" P.I. (using value in 4 above)	-2.5
7. PVN, according to McLeod's equation	-1.5
Estimated Asphalt Stiffness (t = 10,000 sec., and T = -4°F)	
1. Van der Poel Nomograph & Pfeiffer and Van Doormaal P.I. (Fig. 3)	3 kg/cm^2
2. Van der Poel Nomograph & corrected P.I.	50 kg/cm^2
3. Heukelom and Klomp Modified Nomograph and Pfeiffer and Van Doormaal P.I. (see Ref. 9)	2 kg/cm^2
4. Heukelom and Klomp Modified Nomograph and "corrected" P.I. (see Ref. 9)	500 kg/cm^2
5. McLeod's Method	20 kg/cm^2

in estimating asphalt cement stiffness by indirect methods. Haas stated that "the significance of these differences, and to what degree they occur for other asphalts and ranges of loading times and temperatures, has yet to be investigated". Haas mentioned some limitations to the indirect methods for estimating stiffness modulus of bituminous materials. However, he stated that "the indirect methods are a valuable part of the field of asphalt technology". These methods seem to be most useful when used for initial estimates of stiffness modulus.

Use of Limiting Stiffness Concept in the Investigation of Low-Temperature Transverse Cracking

The more direct design approach of limiting stiffness in the asphalt and/or mix has been a natural outgrowth of the field and test section observations, as well as much of the laboratory work. It has been concluded by many authors that the stiffness modulus of the bituminous concrete at low winter temperatures is the major factor governing transverse cracking. They all agree that mixes of lower stiffness modulus should be used to decrease the cracking of bituminous pavements. It seems that this can best be achieved by the use of an asphalt of lower stiffness modulus, either a soft asphalt or an asphalt having improved lower temperature sensitivity, i.e., an asphalt with a P.I. of zero or higher.

McLeod (13) examined a variety of data from Canadian test roads, and has concluded that cracking will occur if the stiffness of a mix in service falls within the range of 1×10^6 to 2×10^6 psi (7×10^4 to 1.4×10^5 kg/cm^2) at the minimum temperature encountered at a depth of 2 in. This stiffness value is for a dense, well-graded mix ($C_v = 0.88$) at 20,000 seconds loading time, and is determined from McLeod's modification of the stiffness nomograph (Fig. 8). As a result, he has prepared a tentative design guide for maximum moduli of stiffness for various temperatures, as shown in Table II

TABLE II

MAXIMUM MIX STIFFNESS FOR SELECTING ASPHALT CEMENT GRADE (AFTER MCLEOD)

Minimum Temp. at 2" Depth	Stiffness Modulus, psi	
	Cracking Expected	Cracking Eliminated
$-40^{\circ}F$	1,000,000	500,000
$-25^{\circ}F$	700,000	300,000
$-10^{\circ}F$	400,000	200,000
$+10^{\circ}F$	100,000	50,000

The table shows the levels of stiffness at which cracking is expected and the levels at which cracking should be eliminated. The latter is a design guide which essentially incorporates a "safety factor" of 2.0 to account for hardening in service. McLeod has translated these criteria into an asphalt cement selection guide, as shown in Fig. 9, for various levels of penetration index. This guide is based on a correlation

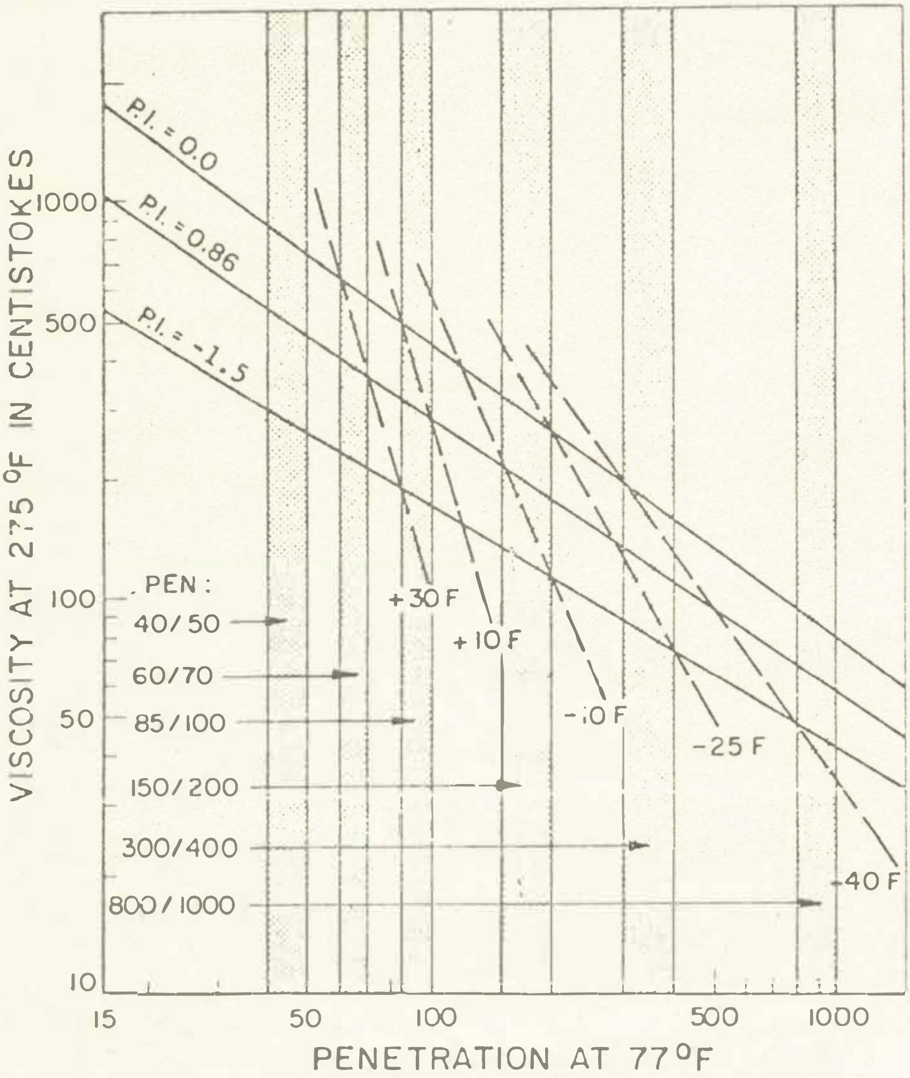


Figure 9. Selection of Asphalt Cement Grade for Various Design Temperatures (After McLeod)

between viscosity at 275^{O}F and penetration at 77^{O}F. The diagram shows, for example, that to avoid cracking for a minimum temperature of -40^{O}F an asphalt cement of P.I. = 0.0 should not be harder than 300 penetration at 77^{O}F. In summary, McLeod suggested that the selection of the original asphalt cement should be primarily guided by: (1) its penetration value at 77^{O}F, (2) its penetration-viscosity number (PVN), and (3) the minimum pavement temperature. He further emphasized that if higher temperature stability requirements are not met, a less desirable asphalt cement would have to be chosen and some cracking tolerated.

In Ontario, Fromm and Phang (4) have performed a series of calculations similar in concept to those of McLeod for specifying the grade of asphalt that should be used for a given surface temperature. Their selection guide, as shown in Fig. 10, is based in part on thin film oven test residues. They assumed a critical stiffness of 1.38 x 10^{8} N/m^{2} (20,000 psi) with a loading time of 2.8 hrs. (10,000 sec.). McLeod's method of calculating stiffness and PVN was used in this study. Phang has further suggested, as have others, that the minimum expected temperature should be chosen on a probabilistic basis.

In the St. Anne Test Road conducted by Shell Canada and the Manitoba Department of Highways, observations of cracking frequency and analysis of the rheological properties of the bitumens using Van der Poel nomograph were carried out. Burgess, et al (3) concluded that the critical stiffness of the bitumen was 2.4 x 10^{8} N/m^{2} (2500 kg/cm^{2} or 35,550 psi) for 0.5 hr. loading time at a temperature of -40^{O}F. This 0.5 hr. loading time corresponds to a cooling rate of 10^{O}C per hour.

Haas (3) has examined the stiffness implications of a variety of asphalt cement specifications in Canada and the U.S. together with some

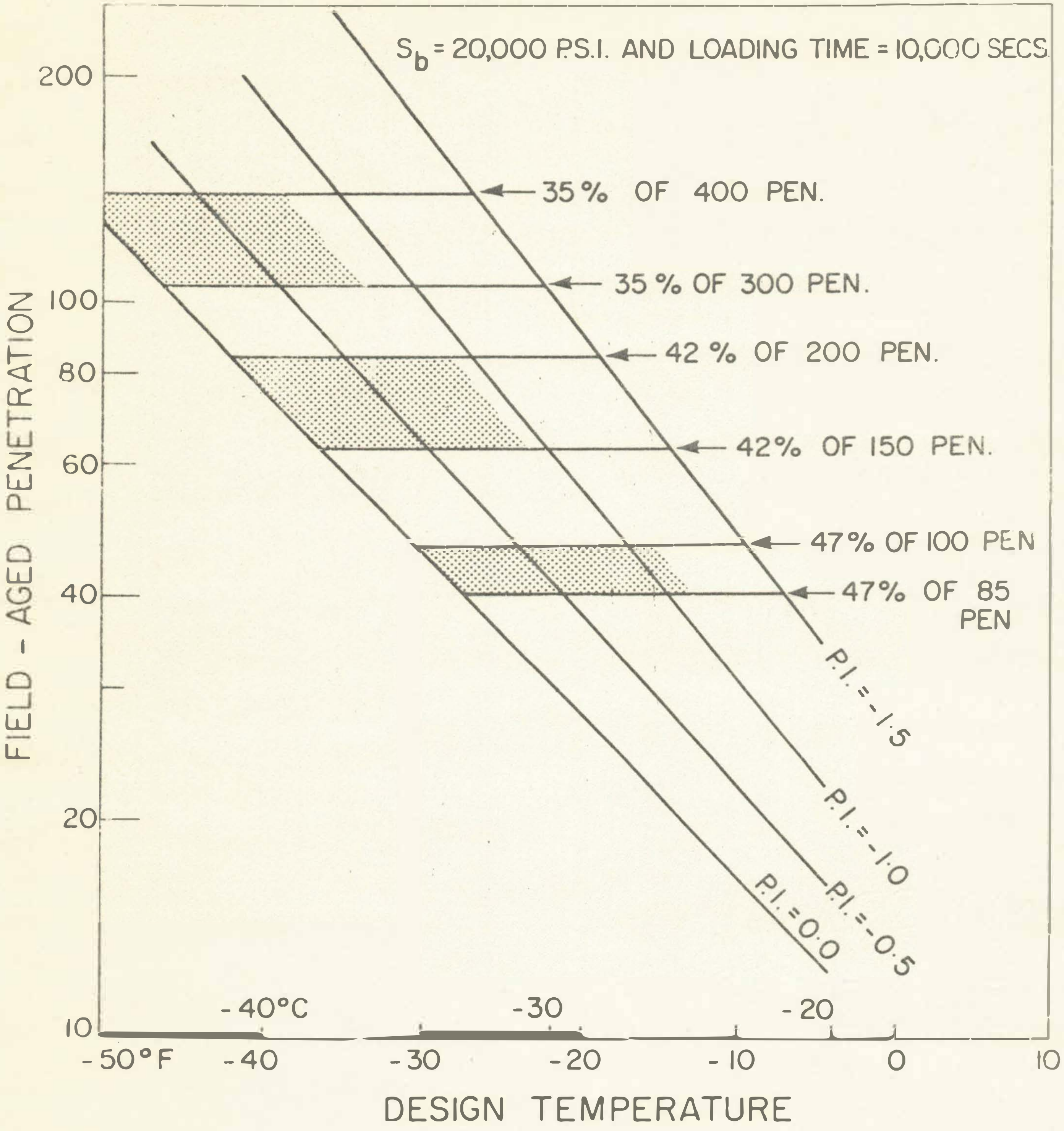


Figure 10. Selection of Asphalt Cement Grade for Various Winter Design Temperatures, 1% Basis (after Fromm and Phang)

values from previous investigations, the results have been compared with McLeod's limits. An example is shown in Fig. 11 for 10°F. All the findings indicated that McLeod's limits are satisfactory.

Since different investigators have chosen different loading conditions for their proposed limiting stiffness moduli, Lefebvre (12) has reduced these values to the same loading time of 0.5 hr. with the aid of McLeod's modification of Van der Poel's nomograph. The results are shown in Table III. Lefebvre agreed on the McLeod's proposed design stiffness criterion which employs a factor of safety. Hajek and Haas (7) referred to experiments showing that indirect method of estimating stiffness are satisfactory, and considered McLeod's procedure to be the best indirect method. Hajek and Haas found it advantageous to use the stiffness modulus of the bitumen as the basis for predicting the frequency of low-temperature cracks.

TABLE III

COMPARISON OF MAXIMUM STIFFNESS MODULI (AFTER LEFEBVRE)

Investigator	Maximum Stiffness	Loading Time in hr.	Equiv. Max. Binder Stiffness at 0.5 hr. Loading Time
Burgess et al	2,5000 kg/cm^2 (Binder)	0.5	2500 kg/cm^2
Phang	20,000 psi (Binder)	2.8	2500 kg/cm^2
McLeod	1,000,000 psi (Mix)	.6	1000 kg/cm^2

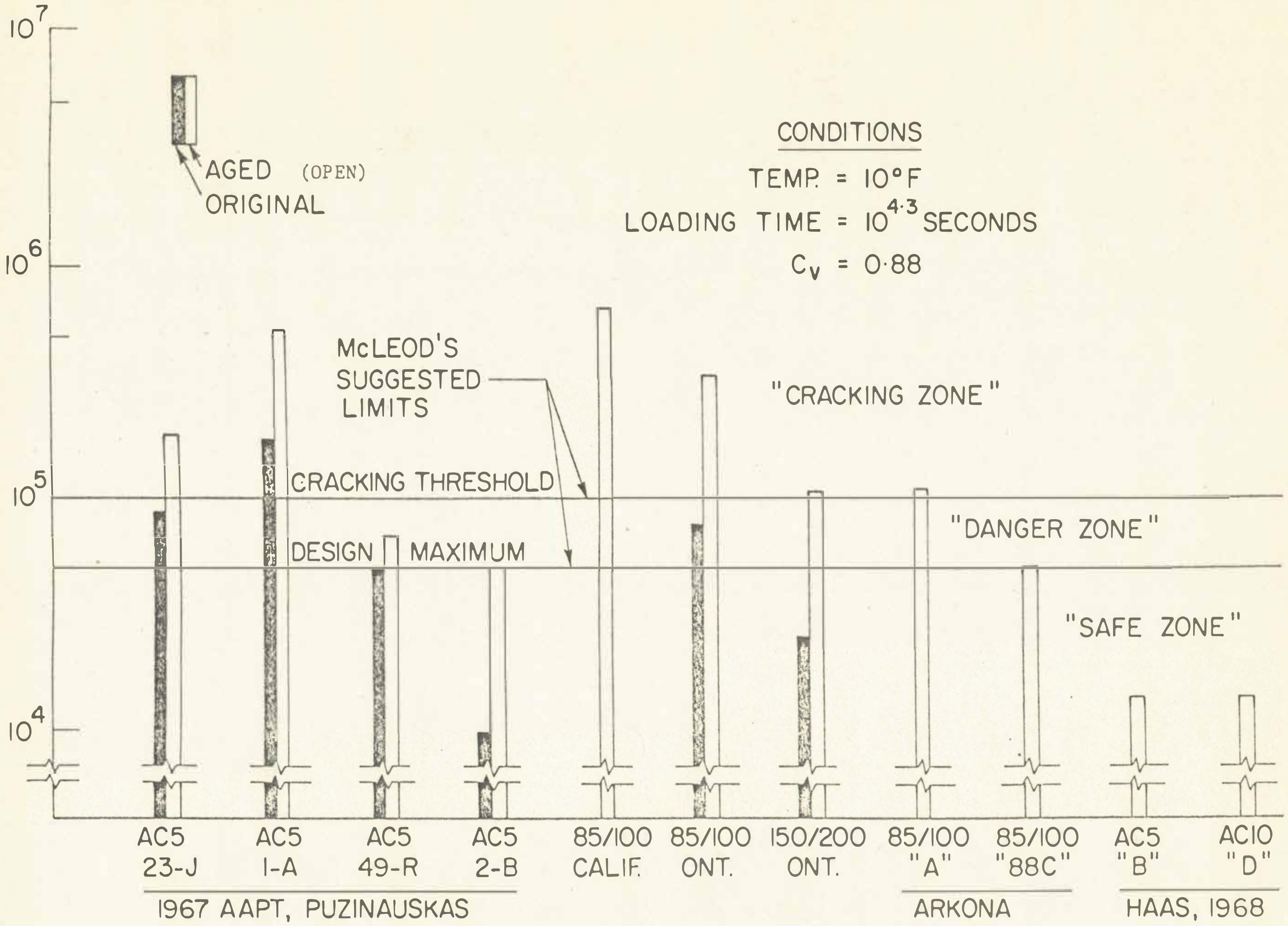


Figure 11. Comparison of Possible Stiffness for Mixes made with Various Asphalts with McLeod's Suggested Stiffness Limits (after Ref. (3)).

It should be noted that the results reported by many investigators (16, 2) indicated that asphalts recovered from uncompacted field mixes may exhibit premature hardening characteristics unless special sampling procedures are used and, therefore, the physical properties of such asphalts may not be indicative of the actual properties of asphalts within newly constructed pavements.

The foregoing discussion shows that a design approach using a limiting asphalt stiffness modulus is reasonable and provides some very useful quantitative guide lines. While most investigators agree on this, they do not all agree on the method to be used for determining binder and/or mix stiffness, i.e., either indirectly by nomograph procedures or by direct testing. Haas (6) found that the indirect methods of estimating stiffness modulus are very quick and easy to use. In his discussion on the use of these indirect methods, he indicated some limitations in both their use and in the application of the results that should be kept in mind. However, he concluded that these methods are most useful for initial estimates of stiffness modulus.

CHAPTER III

TEST RESULTS AND DISCUSSION

Introduction

This study is a preliminary investigation of the low-temperature behavior of Oklahoma asphalt cements and their effect on or contribution to transverse cracking of flexible pavements. This behavior of an asphalt cement, as characterized by its "stiffness modulus", is considered an indication of the sensitivity of a given pavement mixture to cracking. The stiffness modulus of an asphalt binder and/or an asphalt mix at low temperature can be determined quantitatively from certain properties of the binder and the use of charts and nomographs, as discussed previously in the literature review.

There is, apparently, general agreement among investigators that McLeod's method of determining stiffness modulus is a satisfactory approach and McLeod's proposed design stiffness criteria for -40^{0}F service temperature have been correlated with actual field performance. Both the McLeod and Van der Poel method of determining stiffness moduli of asphalt cement were used in this study.

The use of -40^{0}F as a service temperature for calculating stiffness moduli of binders and paving mixtures in Oklahoma may appear questionable. However, this temperature seems to have been arbitrarily selected and does not necessarily represent the minimum winter temperature of more northern areas at which transverse cracking occurs. Studies in Canada by Shields, et al (16) on electronically monitored test sections constructed with 200-300 penetration asphalt cement indicated that transverse cracking occurred at pavement surface temperatures as low as -4.5°F when the air temperature was -16°F. This is well above record low temperatures experienced by many places in the northern and central areas of Oklahoma.

Thus, it appears reasonable to use these criteria as a basis for comparing the rheological and consistency properties of Oklahoma asphalts with those of asphalts used in more northern regions, where transverse cracking is more prevalent. In the event that a more detailed study of these properties becomes warranted, similar procedures and techniques could be used to determine stiffness modulus values at temperatures considerably above -40°F.

This study is divided into three parts. These are:

1. determination of the stiffness moduli of various 85-100 penetration grade asphalt cement samples (31 samples) secured from different sources in Oklahoma (Table IV),

2. determination of the stiffness moduli of three penetration grade asphalt cement samples (91, 124, and 160 penetration). These samples were prepared by blending 85-100 penetration grade asphalt cement with an approximately 500 penetration flux material (Table V), and

3. determination of the stiffness moduli of asphalt mixtures prepared in accordance with OHD-Type C surface mixture specification and having an asphalt content of 5.0 per cent (Table VI).

The test results are discussed and compared to the limiting stiffness values reported in the literature for the same conditions of temperature and rate of loading.

TABLE IV

TEST DATA AND STIFFNESS MODULI OF OKLAHOMA ASPHALT CEMENTS

Minimum Winter Temperature = -40°F
Time of Loading in Secs. = 20,000 (5.55 hr) - Assumed

Sample No.	Sample Ident. No.	Ring & Ball Soft. Pt., $T_{R\&B}$, °F	Penetration		Viscosity		Penetration Index or PVN		Stiffness Modulus, kg/cm^2	
			200gm, 5 sec. 39.2°F	100gm, 5 sec. 77°F	Poises at 140°F	C. St. at 275°F	Pfeiffer & Van Doormaal P.I.	McLeod's PVN	Van der Poel's Method	McLeod's Method
1	14700	116.33	33.12	92.0	1572.6	435.2	-0.474	-0.084	1836.0	1200
2	14719	115.61	27.6	92.0	1200.8	369.0	-0.594	-0.332	2040.0	1300
3	14802	113.63	30.0	86.0	1572.6	362.6	-1.124	-0.471	4000.0	1600
4	14894	112.37	29.0	106.0*	1223.6	380.8	-0.722	-0.152	1530.0	900
5	15043	112.46	29.0	86.0	1503.8	350.0	-1.325	-0.524	5304.0	1700
6	15044	114.89	38.0	92.0	1503.5	429.3	-0.715	-0.104	1836.0	1200
7	15227	117.5	35.0	89.0	1591.6	412.0	-0.383	-0.241	1632.0	1200
8	15385	113.81	31.0	87.0	1487.7	365.4	-1.076	-0.450	3060.0	1500
9	15386	114.35	28.0	87.0	1176.1	327.4	-0.969	-0.613	2652.0	1600
10	15528	112.64	35.0	100.0	1210.3	346.5	-0.855	-0.348	2040.0	1000
11	15572	115.61	36.0	92.0	1584.0	434.9	-0.594	-0.087	2040.0	1200
12	15573	114.8	30.0	89.0	1596.9	432.1	-0.835	-0.157	2350.0	1100
13	15678	114.26	29.0	87.0	1198.7	370.1	-0.984	-0.431	2250.0	1500
14	15814	117.86	37.0	89.0	1580.7	408.5	-0.325	-0.241	1632.0	1200
15	16070	117.41	34.0	93.0	1771.0	424.1	-0.265	-0.130	1530.0	1100

TABLE IV (CONTINUED)

TEST DATA AND STIFFNESS MODULI OF OKLAHOMA ASPHALT CEMENTS

Minimum Winter Temperature = -40°F
Time of Loading in Secs. = 20,000 (5.55 hr) - Assumed

Sample No.	Sample Ident. No.	Ring & Ball Soft. Pt., $T_{R\&B}$, °F	Penetration		Viscosity		Penetration Index or PVN		Stiffness Modulus, kg/cm^2	
			200gm, 5 sec. 39.2°F	100gm, 5 sec. 77°F	Poises at 140°F	C. St. at 275°F	Pfeiffer & Van Doormaal P.I.	McLeod's PVN	Van der Poel's Method	McLeod's Method
16	16132	116.42	36.0	89.0	1576.7	394.9	-0.558	-0.292	2040.0	1300
17	16182	118.04	38.0	88.0	1983.5	435.0	-0.329	-0.121	1632.0	1200
18	16272*	118.4	30.0	83.0*	1993.6	591.4	-0.443	+0.255	1938.0	300*
19	16373	113.18	36.0	96.0	1447.2	406.7	-0.883	-0.171	2244.0	1000
20	16391	116.51	29.0	87.0	1663.6	400.7	-0.610	-0.324	2040.0	1600
21	16392	114.26	35.0	90.0	1354.5	374.6	-0.887	-0.382	2040.0	1600
22	16393	116.87	37.0	90.0	1690.2	462.8	-0.452	-0.062	1430.0	1000
23	16445	110.84	31.0	90.0	1168.7	330.4	-1.486	-0.572	5100.0	1900
24	16586	114.62	33.0	95.0	1449.3	413.5	-0.665	-0.154	2020.0	1200
25	16638	114.98	34.0	93.0	1606.8	430.9	-0.668	-0.084	2040.0	1100
26	16689	113.09	37.0	106.0*	1183.7	360.4	-0.593	-0.230	1520.0	900
27	16739	113.95	33.0	94.0	1335.5	382.2	-0.811	-0.285	2040.0	1300
28	16902	115.93	42.0	99.0	1308.9	371.9	-0.315	-0.250	1520.0	1200
29	17024	119.21	30.0	81.0*	1620.0	435.1	-0.387	-0.275	2040.0	1700
30	17025	114.8	29.0	85.0	1661.5	446.0	-0.959	-0.188	3100.0	1400
31	17026	114.8	28.0	83.0*	1590.9	426.1	-1.026	-0.287	3150.0	1600

*These asphalt cement samples are out of the common penetration grade of asphalts used in hot-mix paving operations in Oklahoma (85-100 penetration)

TABLE V

DETERMINATION OF STIFFNESS MODULI OF OSU ASPHALT CEMENT SAMPLES

Minimum Winter Temperature = -40°F (-40°C)
Time of Loading in Seconds = 20,000 (5.55 hrs) - Assumed

Sample No.	Ring & Ball Soft. Pt., $T_{R\&B}$, °F	Penetration		Viscosity		Penetration Index or PVN		Stiffness Modulus, kg/cm^2	
		200gm, 5 sec. 39.2°F	100gm, 5 sec. 77°F	Poises at 140°F	C. St. at 275°F	Pfeiffer & Van Doormaal P.I.	McLeod's PVN	Van der Poel's Method	McLeod's Method
1	112.06	26.0	91.0	1465.0	387.6	-1.236	-0.283	5100.0	1500
2	107.24	34.0	124.0	939.3	325.0	-1.202	-0.196	2650.0	800
3	102.74	44.0	160.0	652.3	268.8	-1.289	-0.155	2450.0	110

TABLE VI

DETERMINATION OF STIFFNESS MODULI OF OSU BITUMINOUS MIXTURES

Minimum Winter Temperatures = -40°F (-40°C)
Time of Loading in Seconds = 20,000 (5.55 hrs)- Assumed

Specimen No.	Total Vol., V_T, cm^3	Air Voids, %	Wt. of Bitumen, W_b, gm	Specific Gr. of Bit., S_b	Volume of Bitumen V_b, cm^3	Voids in Mineral Agg., % VMA	Vol. Cont. of Agg., C_v	Corrected C_v (C'_v)	Stiffness Mod. of Asphalt, kg/cm^3	Av. Stiff. Mod. of Mix, kg/cm^3
91-5-1	426.10	4.382				16.688	0.871	0.859		
91-5-2	427.50	4.621	52.63	1.0037	52.436	16.887	0.871	0.857	1500	116,680
91-5-3	428.58	4.593				16.828	0.872	0.858		(1.66×10^6) psi
124-5-1	427.55	2.913				15.231	0.873	0.874		
124-5-2	429.52	5.891	52.63	0.9993	52.667	18.153	0.870	0.846	800	84,370
124-5-3	428.21	4.070				16.369	0.872	0.863		(1.2×10^6) psi
160-5-1	427.99	4.333				16.666	0.871	0.860		
160-5-2	429.90	4.836	52.63	0.9971	52.783	17.114	0.871	0.855	110	26,015
160-5-3	425.84	3.978				16.373	0.871	0.863		(3.7×10^5) psi

Discussion of Test Results

As pointed out in the literature review, McLeod's design criteria shown in Table II were determined for a dense, well-graded mix with a C_v value of 0.88. By interpolation in Fig. 5, critical and safe binder stiffness moduli at -40°F were established as shown in Table VII.

TABLE VII

CRITICAL AND SAFE ASPHALT BINDER STIFFNESS MODULI AT -40°F AS INTERPRETED FROM MCLEOD'S DESIGN CRITERION

Condition	Stiffness Modulus, kg/cm^2	
	Mix	Binder
Cracking Expected	70,307 (1,000,000 psi)	286.4 (4,073 psi)
Cracking Eliminated	35,154 (500,000 psi)	97.1 (1,335 psi)

By comparing the calculated stiffness moduli shown in Table IV with these interpreted critical binder stiffness moduli, it is apparent that none of the 31 asphalt samples meets the design criteria suggested by McLeod. This indicates that the consistency of the Oklahoma 85-100 penetration grade asphalt cement is such that transverse pavement cracking cannot be avoided at this low temperature. The selection guide of asphalt cement grades for various design temperatures shown in Fig. 9 also indicates that the 85-100 penetration grade asphalt should not be employed in pavements that will be subjected to a temperature of -10°F (-23.3°C) during its service life. Additional confirmation of this can be obtained by determining the stiffness modulus at this temperature and comparing it with the values listed in McLeod's design guide, Table II.

The data shown in Table V indicate that the prepared asphalt Samples 1 and 2 are considered to be hard asphalts since the stiffness moduli of these samples highly exceed McLeod's maximum limiting stiffness value. On the other hand, Sample 3 (160 penetration) seems to be less sensitive in regard to low-temperature pavement cracking. The stiffness modulus of this sample is less than the limit at which cracking could be expected, but it is slightly higher than the safe stiffness modulus suggested by McLeod.

The laboratory mixtures used in this study incorporated the penetration grade asphalt cements listed in Table V and locally available aggregates. The aggregates consisted of a crushed limestone, limestone screenings and coarse and fine river sands. These aggregates were combined to meet the approximate mid-point gradation stipulated by the OHD-Type C surface course specifications and were mixed with 5.0 percent (total weight basis) of the respective penetration grades of asphalt cement. For the 85-100 penetration grade, this amount of asphalt was the approximate optimum content for the mixture. Three specimens were molded from each of the prepared mixtures in accordance with the procedures outlined in OHD-L-8 (11). Air void content for each compacted specimen was determined using the bulk specific gravity of the specimen and the maximum specific gravity of the mixture (ASTM D2041). The results of the determination of stiffness moduli for these laboratory mixtures is shown in Table VI. The moduli of the first two specimen groups are considerably above the critical limit of Table VII. The third specimen group had a stiffness modulus lower than that suggested by McLeod to eliminate cracking. Thus, the 150-200 penetration grade asphalt cements from this source could be used in pavements subjected to temperatures as low as -40°F. This implies, of course that the paving mixture would have the requisite properties, e.g., stability, at higher temperatures.

CHAPTER IV

CONCLUSIONS

The desigh approach of using limiting stiffness values for the selection of asphalt cements has considerable merit if transverse pavement cracking is a problem. The simple nomographic procedures summarized in this report can be adapted for hot-mix asphalt concrete mix design in Oklahoma and can be used to select the appropriate binder and mixture for specific low-temperature conditions. A particular advantage of this approach is that it can identify asphalt cements having suitable low-temperature characteristics to mitigate or reduce cracking from standard laboratory test results.

Current methods of mix design are primarily concerned with the properties and behavior of the paving mixture at a maximum expected service temperature. However, the research attention given to transverse pavement cracking in northern regions during the past fifteen years and the apparent manifestation of this problem on Oklahoma highways indicates the need for low-temperature design supplements or modifications.

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