NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **59**

RELATIONSHIP OF ASPHALT CEMENT PROPERTIES TO PAVEMENT DURABILITY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
BITUMINOUS MATERIALS AND MIXES
(HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. JUNE 1979

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest to materials engineers, construction engineers, designers, and others seeking information on factors affecting the performance of bituminous pavements. Detailed information is presented on how various properties of asphalt cement influence pavement performance.

Administrators, engineers, and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems. Syntheses from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

In recent years, apparent changes have evolved in the physical properties of asphalt cements used in pavement construction. Some of these properties are not controlled or are controlled only partially by AASHTO specifications. This report of the Transportation Research Board reviews all available information relating durability and performance of asphaltic concrete mixtures to the properties of the asphalt cement. Recommendations for improved test procedures and criteria are included. The report concludes that hardness of the asphalt is the property most important to pavement performance.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Bob H. Welch, Associate Engineer of Materials and Construction, Transportation Research Board, assisted the Special Projects Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

RELATIONSHIP OF ASPHALT CEMENT PROPERTIES TO PAVEMENT DURABILITY

SUMMARY

Early asphalt pavement construction was essentially rule-of-thumb practice resulting in some excellent pavements as well as some failures. Eventually, test methods were developed to measure properties of asphalt cement after plant mixing and service in pavements.

This synthesis brings together information from studies on the relationship of asphalt cement properties to pavement durability. A literature search revealed studies of such properties as penetration, viscosity, temperature susceptibility, shear susceptibility, stiffness modulus, ductility, chemical composition, and asphalt-aggregate interactions. Many results are given in this synthesis.

The research included uncontrolled, semicontrolled, and fully controlled field tests. In the semicontrolled and fully controlled tests, a relatively small amount of distress was reported. This may be because the specifications resulted in higher quality and more uniform asphalt for these projects. Improved mixture design and construction control could be other significant factors. The large amount of distress for the uncontrolled test sections was caused by asphalt of too low penetration or too high viscosity as well as excessive hardening of the asphalt during construction or in service. Over-all, performance data point out the importance of selecting the proper grade of asphalt for environmental and traffic loading conditions.

Among the concepts that have been proposed or used to control transverse cracking are low-temperature penetration, low-temperature ductility, penetration-viscosity relationships, and direct and indirect testing of mixtures to determine asphalt and mixture stiffness. The indirect testing methods include Penetration Index by van der Poel, Penetration Index modified by Heukelom, and Penetration-Viscosity Number (PVN) by McLeod.

The primary conclusion of this synthesis is that hardness of the asphalt is the one property most closely associated with pavement performance. Hardness depends on asphalt grade, mixture design, temperature susceptibility characteristics, susceptibility to hardening during hot-plant mixing and construction, rate of hardening in service, and asphalt-aggregate interactions. Tests to measure and control hardening of asphalt cements during hot-plant mixing and in service include thin-film or rolling thin-film tests, consistency tests to measure temperature susceptibility characteristics, and microfilm aging tests.

Recommendations include development of (a) criteria for selecting asphalt cements to accommodate pavement design and temperature and traffic loading conditions, (b) a standard method for sampling existing pavements, (c) a standard indirect method of determining stiffness modulus, and (d) a standard method for measuring low-temperature properties directly. Tests based on inverse gas-liquid chromatography should be explored further as a means of determining asphalt-aggregate interactions that affect the hardening of asphalt.

CHAPTER ONE

INTRODUCTION

EARLY HISTORY OF ASPHALT PAVING AND PAVEMENT PERFORMANCE

From 1876 to the mid-1890s, Trinidad Lake asphalt was the primary source of asphalt used for pavement construction in the United States. In the 1890s, Bermudez Lake asphalt from Venezuela came into use. The promoters of the lake asphalts exercised a monopoly and attempted to restrict the use of other asphalts, primarily those refined from domestic crude oils, which became available around 1900. Restrictive specifications were written merely to identify the lake asphalts and restrict the petroleum asphalts.

The early use of asphalts in asphalt-aggregate mixtures for pavement construction was essentially a rule-of-thumb practice resulting in some excellent pavements as well as some that were partial or total failures. Engineers and chemists realized that test methods were needed and that specifications had to be written to control asphalt quality and prevent indiscriminate use of inferior or untried materials.

VOLATILITY OF ASPHALTS DETERMINED IMPORTANT

The native asphalts were solid or semisolid materials, and it was necessary to reduce their consistency by adding petroleum fluxes to make binders soft enough for paving mixtures. To reduce hardening of the asphalt during plant mixing and in service, numerous tests were devised to control volatility of the fluxed asphalts or, in some cases, the fluxes themselves. Oven heat tests at temperatures of 212 F (100 C), 240 F (121 C), 325 F (163 C), or 400 F (204 C) were used, and the time of heating varied up to 7 hours. A standard loss-on-heating test was not adopted by ASTM until 1911. At the same time, the penetration test, which had been used by some laboratories since 1888, was made a standard method by ASTM. These tests were the first attempts to control asphalt hardening. As a matter of interest, the method for determining bitumen (soluble in carbon disulfide) also was adopted as an ASTM standard in 1911. Again, its primary use was to identify native asphalts by observing the amount and character of the inorganic material.

HIGHWAY RESEARCH BOARD ACTIVITY

In the 1930s, the Highway Research Board (now the Transportation Research Board) organized a committee to investigate the relation of asphalt properties to pavement durability (*1*). The primary objective was to acquire information on which to base more rational specifications and improved test methods. The committee indicated that the existing specifications for asphalt materials were not satisfactory because they did not depend on characteristics of known relation to service behavior. The tests in use identified certain asphalts of known satisfactory service behavior or restricted the source or method of production. To define the problem more closely, the committee had to collect and study information on the causes of failures and the reasons for good performance. The information had to concern asphalt as well as other significant factors regarding service behavior.

The committee's primary means of exploring service behavior was through a questionnaire. A summary of 91 replies brought out these facts:

- Failures or unsatisfactory performance from the use of poor-quality asphalt occurred in all sections of the country.
- Cracked asphalts appeared to be more troublesome than uncracked asphalts. (Cracked asphalts were produced from petroleum by high-temperature and high-pressure refining methods.)
- Among the asphalt cements used, the harder grades appeared to be the chief source of unsatisfactory pavement performance.
- Age hardening and increased brittleness in the asphalt were found to be the changes that most frequently produced unfavorable results.
- Cracking and raveling appeared to be the principal failures attributed to poor-quality asphalts.

ABSON RECOVERY METHOD DEVELOPED

One of the most important breakthroughs in the development of methods for testing the properties of asphalt cements after plant mixing and service in pavements was the Abson recovery method, developed in 1933 (*2*). Initially, benzene was used to extract asphalt from mixtures, and the asphalt was recovered from the solution by distillation in the presence of an inert gas. Later trichloroethylene was adopted as an alternate solvent.

The Abson method had been preceded by a method proposed by Bateman and Delp in 1927. In this method, carbon disulfide was used for extracting asphalt from paving mixtures, and the asphalt was recovered from the solution by vacuum distillation (*3*). Because there was some indication that carbon disulfide hardened the asphalt during extraction and recovery, the method was not used extensively.

In 1936, Bussow proposed a method of recovering asphalt from a solution of asphalt and benzene by atmospheric distillation (*4*). The pros and cons of the Bussow and Abson methods were debated for some time, but ultimately the Abson method was adopted as the standard (ASTM Standard Method D 1856).

Since the development of the Abson recovery test in 1933, numerous studies have determined the properties of asphalt cements after hot-plant mixing and pavement aging. Researchers generally recognize that the properties of an asphalt recovered from an aged pavement may differ from those of the asphalt existing in the pavement before extraction and recovery. Dissolving the asphalt for extraction and using the heat treatment during recovery could destroy the asphalt structure that may develop with aging. Traxler and Schweyer showed that some asphalts age-harden, or develop a structure, more rapidly than others (*5*). Disregarding the fact that there may be unknown age-hardening effects, the Abson method has been valuable in studying changes in asphalt properties during plant mixing and aging in the pavement and in relating the properties to pavement durability. Anyone planning to use the Abson recovery method should be aware that any deviation from the standard method may affect the results.

OBJECTIVES AND LIMITATIONS OF THE SYNTHESIS

During the past 15 years, new methods of measuring the fundamental rheological properties of asphalt cements have been developed and, in many cases, standardized. In some studies, these new tests have been used to correlate asphalt properties with pavement performance. The purpose of this synthesis is to bring together existing information on the relationship of asphalt cement properties to pavement durability. The following objectives and limitations were considered in developing the scope of this synthesis:

- Review, analyze and report on significant studies and findings that relate the properties of asphalt cements to pavement durability.
- Include the development of test methods and their use in specifications and determine what requirements for asphalt cements can now be used to assure improved pavement durability.
- Limit the findings to asphalt cements used in hot plant-mixed pavements.
- Limit the literature search to information relating properties of asphalt cements to pavement durability, and do *not* research the following factors, which are or may be related to the problem: (a) aggregate—type, grading, and quality; (b) mixture design—proper asphalt content; (c) quality control—uniformity of plant mixtures; (d) plant mixing procedures; (e) compaction—final road density and mixture void content; (f) traffic; (g) environment—temperature.

The literature strongly supports the fact that void content of compacted asphalt mixtures has a predominant effect on hardening of asphalt in service. When known, the void effect will be indicated for the various studies described.

LITERATURE SEARCH

The literature search included studies showing information on (a) original asphalt cement properties, (b) recovered asphalt cement properties after service in pavements, and (c) test methods and criteria that might or might not predict service performance.

The following asphalt properties and their relation to pavement durability were researched:

1. Penetration—one or more temperatures.
2. Viscosity—one or more temperatures.
3. Temperature susceptibility—change in consistency with change in temperature. Temperature susceptibility = $\frac{\log \log n_2 - \log \log n_1}{\log T_2 - \log T_1}$
   n_1 = viscosity at temperature T_1
   n_2 = viscosity at temperature T_2
4. Shear susceptibility. Shear susceptibility = tangent of the log viscosity-log rate of shear curve.
5. Stiffness modulus—various methods.
6. Ductility—normal and low temperatures.
7. Chemical composition.
8. Asphalt-aggregate interactions.

PAVEMENT DURABILITY

Pavement durability, for purposes of this synthesis, is defined as the resistance of asphalt pavement surface to change during service. The following forms of distress or pavement damage were considered in the attempt to relate asphalt cement properties to pavement durability:

1. Fatigue cracking.
2. Low-temperature (thermal) cracking.
3. Shrinkage cracking.
4. Distortion—rutting and shoving.
5. Disintegration—raveling and loss of matrix.
6. Moisture—effect on cracking and disintegration.

Asphalt durability can be defined in a number of ways. For instance, in 1943 Hveem defined it as the ability of asphaltic materials to retain their original properties (*6*). He cautioned that before one seeks to cure all the ills of bituminous pavements by adjusting the properties of the asphalt, one must identify those troubles for which the asphalt alone is responsible. Hveem indicated that the most consistent differences between the performance of asphalts are shown by pavement cracking and disintegration of the surface by abrasion. Hveem divided pavement deterioration into three failure categories:

1. Deformation caused by traffic.
2. Cracking due to traffic and material properties.
3. Disintegration due to traffic, material properties, and environment.

Thus material properties are given as major contributors to pavement deterioration.

In NCHRP Report 39 (*7*), Finn restates that durability of asphaltic concrete has been defined as the long-term resistance to the effects of aging. For asphalt concrete pavements, good durability can be described as the apparent ability to provide long-term performance without abnormal amounts of cracking and raveling. Finn points out, as have many others, that asphalts and aggregates could have good durability but because of poor mixture design or construction the pavement would not be durable. Conversely, an asphalt of poor durability could result in an acceptable pavement provided special precautions are taken with mixture design and construction practices.

Finn (*7*) reviewed some of the results of research associated with the hardening of asphalt in service and the consequences of the hardening on pavement performance. The net results of the investigations indicate that the harder asphalts (i.e., low penetration, low ductility, and high softening point) tend to have the poorest performance record. Although external factors influence the change in asphalt properties during service, they are subject to some control by the engineer responsible for the design and construction of the asphalt surfacing.

CHAPTER TWO

REVIEW OF LITERATURE AND PRACTICE

The literature contains the following four potential sources of information showing the relation of asphalt cement properties to pavement durability:

1. Pavements constructed under normal contract procedures, with performance surveys and tests on representative pavement samples to determine the properties of the asphalt after one or more periods of service. Generally only results of specification tests on the asphalt were available.
2. Pavements constructed under normal contract procedures. Pavement performance and tests on the original and recovered asphalts were known or determined.
3. Pavements constructed under normal contract procedures but with asphalts of different types and sources substituted for the construction asphalt in trial sections. Pavement condition surveys and tests on asphalts before and after various periods of service were determined.
4. Planned experimental road trials using asphalts of different types and sources and constructed under controlled conditions.

Pavements in categories 1 and 2 are considered uncontrolled road trials, because they probably would have been constructed by different contractors and included some or all of the variables listed previously. Road trials constructed in category 3 are considered semicontrolled and those in category 4 fully controlled.

TABLE 1

TEST RESULTS OF ASPHALTS FROM GOOD AND POOR PERFORMANCE PAVEMENTS (*6*)

	Good Pavement		Poor Pavement	
	Original	Recovered	Original	Recovered
Penetration, 77 F (25 C)	56	34	42	13
Ductility, 77 F (25 C) cm	100+	15	113	3.2

UNCONTROLLED ROAD TRIALS

Following the development of the Abson method for recovering asphalt from pavement samples, numerous studies were made to determine the properties of asphalt from pavements that had been in service for various periods of time and were in varying states of distress. One of the earliest studies was reported in 1936 by Rader (*8*). Two sheet asphalt pavements constructed in 1927-1928—one in good condition and one showing appreciable cracking—were selected for study to determine whether the results of laboratory tests could be correlated with performance as shown by resistance to cracking. The pavements consisted of 1½ in. (38 mm) of sheet asphalt over 1½ in. (38 mm) of binder course laid on a concrete base. The pavement in good condition was constructed with 56 penetration asphalt from a Colombian crude. The pavement showing appreciable cracking was constructed with a 42 penetration asphalt from a Mexican source.

Composition tests and several physical tests were performed on the pavement samples. The asphalt was recovered by the Abson method. Results of penetration and ductility tests are given in Table 1. Rader concluded that, other factors being equal, those mixtures containing the highest penetration asphalt consistent with necessary stability would prove most resistant to cracking at low temperatures.

In 1937, Rader reported tests made on six additional pavements constructed in 1926-1929 (*9*). With one exception, the results confirmed earlier findings that higher penetration asphalts were associated with the good pavements.

In 1937, Hubbard and Gollomb reported a study showing the effect of asphalt hardening on the development of cracks in asphalt pavements (*10*). The eight pavements that were rated good to excellent had penetrations of the recovered asphalts that ranged from 26 to 51. One pavement rated serviceable after 47 years of service was constructed with 60-70 penetration fluxed Trinidad Lake asphalt, and the recovered asphalt had a penetration of 55. Asphalt cements of 50-60 penetration were used for the other pavements. Twelve of the pavements were rated bad because of cracking and in some cases disintegration. The penetration of the original asphalts ranged from 41 to 53, and the penetration of the recovered asphalts ranged from 10 to 22. For the pavements studied, the authors concluded:

1. When the penetration of the asphalt cement falls below 20, serious pavement cracking may occur.
2. Some cracking may occur when the penetration is between 20 and 30.
3. High resistance to cracking may occur when a mixture is well-designed and properly compacted and the penetration of the asphalt is well above 30.
4. To ensure long life, one should use as soft an asphalt as possible without reducing stability below the minimum required to prevent displacement under traffic.

A discussion of the Hubbard and Gollomb paper by Baskin and LeBel pointed out that in some Canadian cities the winter temperatures are generally much lower than they are in most U.S. cities (*11*). Canadian engineers recognized that cracking was definitely related to asphalt consistency or penetration of the asphalt cement at low temperatures. They also recognized asphalt's susceptibility to temperature change. Sheet asphalt pavements made with asphalt that was softer and had materially lower temperature susceptibility showed better resistance to cracking.

Powers reported test data for asphalts recovered from Arizona pavements (*12*). Of 12 pavements in Phoenix and Tucson, 6 were rated good to excellent and 6 were badly cracked. The penetrations of the asphalt recovered from 5 of the 6 good to excellent pavements ranged from 12 to 19. For 5 of the 6 badly cracked pavements, the penetrations ranged from 2½ to 6.

Considering that the experiences in Canada and Arizona are typical, it is obvious that lower-penetration asphalts should be used in warmer climates and that higher-penetration asphalts are necessary in colder areas to reduce cracking problems.

In 1937, Rashig and Doyle reported on 30 sheet asphalt pavements in Ohio having varying amounts of distress (*13*). Moduli of rupture and elasticity, mixture composition, density, extraction and recovery of asphalt, and properties of the recovered asphalt were reported for 18 pavements. With one exception, the penetrations of the asphalts recovered from the poor pavements were 25 or less and the ductilities were less than 15. Figure 1 shows the relation between penetration and ductility of the recovered asphalts. As explained later, the consistency of the asphalt must be considered if limiting ductility values are set.

A comprehensive study of asphalt and mixture properties and pavement performance in several states was reported by Miller, Hayden, and Vokac in 1939 (*14*). The study included pavements constructed with 50-60 penetration asphalts from Trinidad Lake and petroleum asphalts from Mexico, Colombia, California, and two unknown sources. The ages of the mixtures at the time of sampling ranged from 1 to 31 years for the pavements in which oil asphalts were used and 7 to 49 years for those made with Trinidad asphalt. The Trinidad asphalt referred to in this study was fluxed Trinidad Lake asphalt. It normally contains about

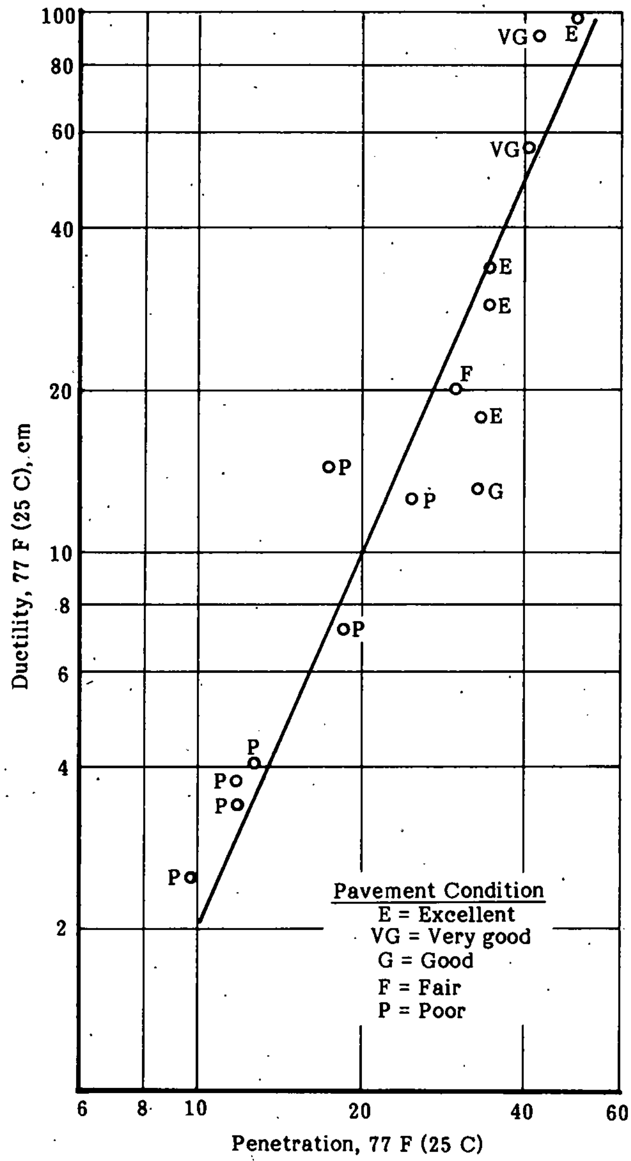

Figure 1. Relation between penetration and ductility of asphalt recovered from sheet asphalt pavements of excellent to poor performance (after 13).

35 percent natural mineral dust, which increases the consistency of the fluxed asphalt. The authors showed that removing the dust by the Abson method allowed appreciably higher penetration bitumen. The following data show the penetration at 77 F (25 C) for fluxed Trinidad Lake asphalts and for the extracted and recovered bitumen:

Trinidad AC	26	37	41	51	77	92
Bitumen	43	59	62	75	127	153

Because of the difference in the consistency of the bitumen recovered from the Trinidad asphalt cement and that recovered from the oil asphalt cement, the data pertaining to each were analyzed and reported separately. Table 2 gives average data for the characteristics of the bitumen and asphalt cement for the cracked, sound, and shoved groups of pavements. Table 2 also gives the number of

TABLE 2

CHARACTERISTICS OF BITUMEN AND ASPHALT CEMENT FOR CRACKED, SOUND, AND SHOVED PAVEMENTS (AFTER *14*)

Group	Number of Projects	Penetration, 77 F (25 C) Original Asphalt Cement	Bitumen	Recovered Bitumen	Ductility 77 F (25 C) Recovered Bitumen (cm)	Softening Point (F)	(C)
From Trinidad mixtures							
Cracked	6	46	69	26	76	149	65
Sound	14	50	73	43	139	134	56
Shoved	5	57	83	55	146	130	54
From Oil asphalt mixtures							
Cracked	17	49	49	18	6	178	81
Sound	18	51	51	29	40	148	64
Shoved	5	55	55	39	70	142	41

projects in which the various source materials were used. In all cases, the asphalt penetration was lowest where the pavement cracked and highest where shoving was encountered.

The authors considered many of the factors that can influence the change in asphalt properties and the relation of the properties to pavement durability or performance. Regardless of the causes, however, the data show that asphalt characteristics have a definite effect on the durability of pavements.

Vokac has shown the following relationship of penetration of the recovered asphalts to pavement performance: When penetration is less than 18, pavements definitely will crack; when penetration is between 18 and 25, pavements are prone to cracking; when penetration is more than 25, pavements generally are free from cracking (see Table 3).

In 1940, Shattuck reported the results of tests on samples of asphalts recovered from sheet asphalt pavements in Detroit, Michigan (*15*). Of the 33 pavements studied, 28 contained Mexican asphalts from several sources of supply. In 29 pavements, 40-45 penetration asphalt was used. In the other four pavements, two 50-55 grade asphalts from California and two from West Texas were used. The California and West Texas asphalts had been in service 5 years; all other pavements had been in service from 10 to 13 years. Table 4 gives the pavement condition and properties of the recovered asphalts.

Shattuck contended that when ductility drops below a certain level, the pavement tends to crack badly, but he did not indicate the effect of hardening or penetration on the ductility values. With the exception of one sample, all the ductility values for asphalt recovered from cracked pavements were less than 10. The penetrations of the same recovered asphalts were less than 20.

Table 3 summarizes the correlation of pavement condition with the physical properties of the recovered bitumen (asphalt). Even though the studies were widely diversified from the standpoint of outside variables other than asphalt grade and source, the relationships of asphalt properties to performance for the various sources are in fair agreement. The effect of environment is evident in the Arizona and Cuba studies.

Halstead reported penetration-ductility relationships based on data from several studies that evaluated pavement performance (*17*). The data were collected from a number of published and unpublished sources and used to establish a limiting penetration—log ductility curve. Asphalts having penetrations and ductilities above the curve were generally associated with better pavement performance, and those falling below the curve may be associated with poor pavement performance. An example of Halstead's data is shown in Figure 2.

TABLE 3

CORRELATION OF PAVEMENT CONDITION WITH PHYSICAL PROPERTIES OF RECOVERED BITUMEN (*16*)

Source of Data	Location of Pavements	Condition of Pavement	Tests on Recovered Bitumen: Penetration 77 F	Ductility 77 F Cm	Softening Point F
Shattuck (15)[1]	Detroit, Mich.	Very good	20+	50+	---
		Good	20+	25+	---
		Badly cracked	20-	25-	---
Thomas (15)	Minnesota	Good[2]	41	---	---
		Fair[2]	26	---	---
		Poor[2]	20	---	---
Hubbard and Gollomb (10)	Ohio, Mich., N.Y., Ind., D.C.	Sound	30+	---	---
		Prone to crack	30-	---	---
		Cracking type	20-	---	---
Vokac (14)	Ohio, Pa., Md., Va., Mo., Ill., Ind., Mich., N.Y., N.J., D.C.	Sound	25+	24+	---
		Prone to crack	18-25	4-24	160-
		Cracking type	18-	4-	160+
Powers (12)	Arizona	Good	10+	10+	160-
		Cracked	10-	10-	160+
Public Roads Administration (*)	Cuba	Good[2]	9	1.5	199
		Cracked[2]	5	0.5	217

[1]Numbers in parentheses refer to the reference list.
[2]Average values.
*Unpublished.

PAVEMENT DURABILITY—EARLY STUDIES

Field performance studies of asphalt pavements during the 1930s and 1940s indicated that asphalts did not all perform in the same manner and that some asphalt properties were related to pavement durability. The initial specified hardness and the hardening of asphalt in the pavement were of major concern. Two developments had a direct bearing on the solution of the problem.

One development was the trend in the late 1930s to specify higher penetration grade asphalts in place of the 40-50, 50-60, and some 60-70 grades in common use. Phelps reviewed the trend toward softer asphalts (*18*). Buchanan had indicated earlier that the use of softer asphalt cements (higher penetration) in hot-laid, plant-mixed pavements would result in better performance, longer life, and less cracking (*19*). He implied that aggregates had proven reliable to produce desired stability in asphalt paving mixtures. There was a trend toward 60-70 or higher penetration asphalts in warmer climates and 151-200 penetration asphalts or SC-6 liquid asphalt in colder climates.

The other development was the effort by several researchers to devise laboratory tests that could predict asphalt quality and, with proper specification requirements, assure better pavement durability. Most of the test methods proposed are described briefly in the following section.

LABORATORY WEATHERING TESTS

Nicholson's Laboratory Oxidation Test for Asphaltic Bitumen

A sample of asphalt was air-blown at 425 F (229 C) using ⅓ cu ft (0.0091 m^3) per min for 15 min (*20*). After air-blowing, the asphalt was tested for penetration and ductility. Asphalts retaining higher penetration and ductility were considered better materials. Another version of the test was to air-blow the asphalt to a penetration of 20 to 25. The asphalt showing the highest ductility was considered best.

Rashig and Doyle's Laboratory Oxidation Test

Samples of asphalt were air-blown at 400 F (204 C) with ⅓ cu ft (0.0091 m^3) per min for 15 min (*21*). The drop in penetration was determined. Those asphalts that retained the highest penetration were considered better materials.

Hubbard and Gollomb's Oxidation Test

Hubbard and Gollomb determined the relative hardening of asphalts when mixed with sand and weathered in the laboratory for different lengths of time at different temperatures (*10*). The asphalt was extracted and recovered by the Abson method. Those asphalts having the highest retained penetration were considered to be more resistant to hardening.

Shattuck's Mixing Test

A 2-kg (4.4-lb) sample composed of 94 percent standard Ottawa sand and 6 percent asphalt was mixed in the laboratory for one min at 275 F (135 C) to 300 F (149 C) (*15*). Then the asphalt mixture was placed in a pan 7 x 11 in. (180 x 280 mm) and heated at a constant temperature of 350 F (177 C) for 30 min. After the mixture cooled, the asphalt was extracted and recovered by the Abson method. The recovered asphalt was tested for penetration, ductility, and softening point. Standard asphaltic concrete and sand asphalt mixtures also were used to evaluate the change in asphalts by this mixing and aging process. A cooperative study with the Bureau of Public Roads and Shattuck was conducted to evaluate results from the thin-film oven test and the Shattuck mixing test (*22, 23*). The changes that occur during the thin-film oven test are similar to the changes that may be expected to occur in laboratory mixing tests such as proposed by Shattuck.

TABLE 4

AVERAGE PROPERTIES OF RECOVERED ASPHALT FROM PAVEMENTS IN VARIOUS CONDITIONS (AFTER *15*)

Pavement Condition	Average Properties of Recovered Asphalt: Penetration 77 F (25 C)	Ductility 5 cm/min. 60 F (16 C)	Ductility 5 cm/min. 77 F (25 C)	Softening Point °F	Softening Point °C
Very good--no cracks	42	110+*	110+	128	53
Very good	34	9.7	59	150	66
Very good-few cracks	26	5.8	28	154	122
Badly cracked	18	1.7	5	175	79
Very badly cracked	8	0.3	1.5	197	92

*California asphalt--5-year service

The Oliensis Test

The Oliensis spot test method was published in 1933 and used extensively as a specification requirement to determine if asphaltic materials had been overheated or cracked during the refining process (*24*). Two grams of asphalt were dissolved in 25 ml of a standard naphtha solvent, and the character of a spot resulting from placing a drop of solution on filter paper was determined. A uniform spot with no visible inner nucleus or ring was termed negative. A nonuniform spot was termed positive and indicated that the asphalt had been overheated or cracked during refining. A few asphalt sources gave an inherent spot due to the presence of waxy or inorganic materials.

The Oliensis test was modified in 1936 to provide a quantitative measure of the degree of heterogeneity (*25*). Increments of xylene were added to the standard naphtha, and the maximum amount needed to change the spot from positive to negative was observed. This amount and the next lowest amount were reported as the xylene equivalent, such as 20-24.

The need for the Oliensis test is shown by a Lewis and Welborn study on the properties of asphalts produced in the U.S. in 1935 (*22*). Thirty-nine samples of 50-60 penetration-grade asphalts and 40 samples of 85-100 penetration-grade asphalts were collected from 27 and 28 refinery sources, respectively. The samples are believed to represent the asphalt cements being supplied at that time. Fourteen asphalts of the 50-60 grade and 15 asphalts of the

85-100 grade gave positive spots with the standard naphtha. Eleven 50-60 and six 85-100 penetration asphalts showed xylene equivalents of 16-20 or higher. The Oliensis test appears to be the most consistent indicator of probable hardening in the thin-film oven test. Asphalts produced by more severe refinery cracking processes, as measured by the xylene equivalent, would fail suggested minimum retained

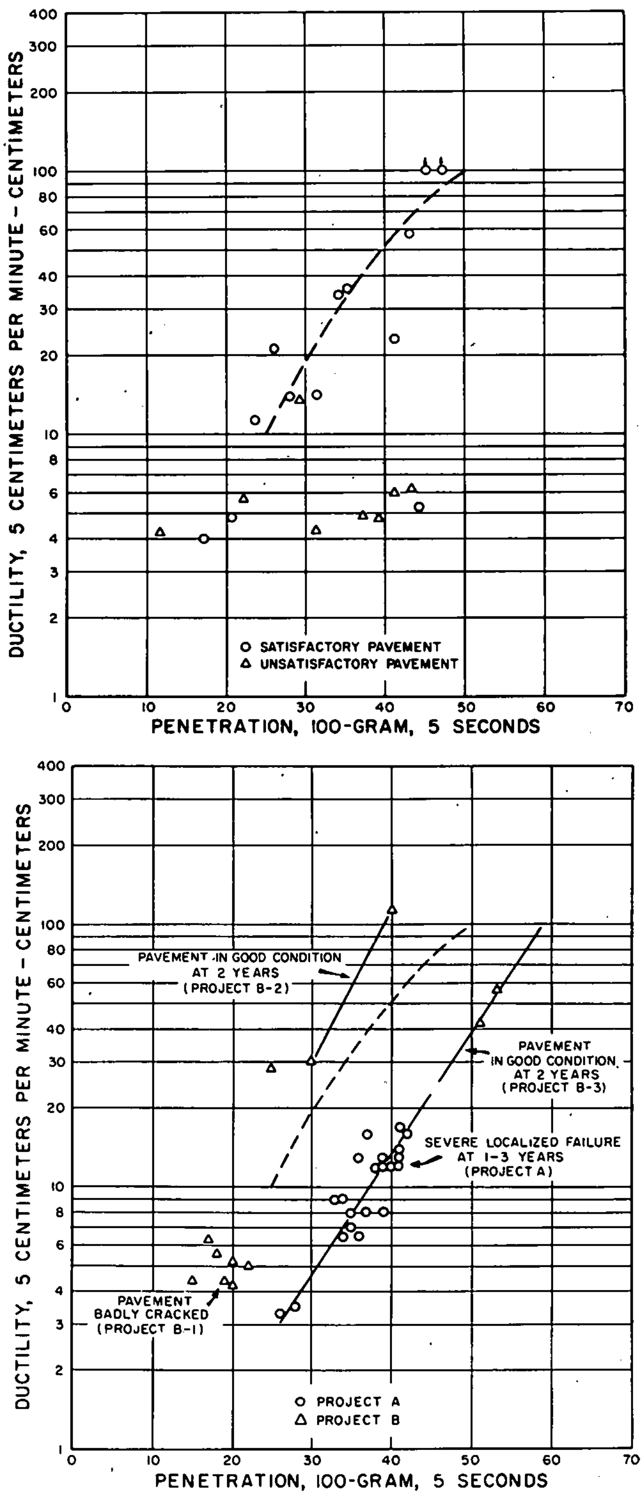

Figure 2. Examples of ductility-penetration relationships for satisfactory and unsatisfactory pavements (17).

penetration and ductility requirements on the thin-film residues.

A study of asphalt cements produced in the U.S. around 1955 showed that 105 of 119 samples of 85-100 penetration asphalt, representing all major sources of supply, had negative results and that, except for two asphalts, all xylene equivalents were less than 12-16. The two asphalts had positive spots with 100 percent xylene, which was probably due to waxy components or some material insoluble in carbon disulfide as indicated earlier. Thus, the importance of the Oliensis test was greatly diminished between 1935 and 1955, primarily because of the petroleum industry's change to new refining methods that eliminated cracked asphalts.

Benson's Microscopic Reactions in Translucent Asphaltic Films

Translucent asphaltic films approximately 0.001 in. (0.025 mm) thick were exposed to natural and artificial light and heat (*26*). The films were observed under the microscope and classified as clear, coagulated, flocculated, wax bodies, checked, or hardened. No direct correlation with pavement performance was found. However, the test was used by one state for specifications purposes.

Lewis and Welborn's Thin-Film Oven Test (TFOT)

In 1940, Lewis and Welborn reported an extensive study of asphalt cement hardening during hot-plant mixing and exposure to weathering (*23*). The study was undertaken to develop a test method that would replace the standard oven loss-on-heating test to predict probable hardening of asphalts during hot-plant mix construction and service in the pavement. The standard test was developed in the era of fluxed asphalts; however when petroleum asphalts came into use and improved methods of refining were adopted, the test was of little value for differentiating among asphalts in terms of volatility and hardening.

A number of attempts were made to develop a better test. Lewis and Welborn studied various methods and, after extensive testing of representative asphalts of 50-60 and 85-100 penetration produced in the U.S. in the mid-1930s, proposed an oven heat test. In this test, a 50 ml sample of asphalt was heated in a ⅛-in. (3-mm) film in a 5.5-in. (140-mm) flat container for 5 hr at 325 F (163 C). The oven and procedure were essentially the same as those used for the standard loss-on-heating test.

Initially, residue from the TFOT was tested for penetration at 77 F (25 C), ductility at 77 F, and softening point (Ring and Ball). The ability of asphalts to retain their original properties as measured by changes during the TFOT offered a means of evaluating the relative durability of asphalts. Proper limits on penetration, ductility, and softening point after heating could be considered requirements for specifications that would control and evaluate durability.

Additional data supporting the development and use of the TFOT were made available in the 1940s, but it was not until 1959 that AASHTO adopted the test as a standard method and modified its specifications to include requirements for a maximum loss in weight and minimum retained penetration and minimum ductility at 77 F (25 C) on the thin-film residue.

ASTM adopted the TFOT as a tentative method in 1960 and as a standard in 1969. Since then, the test has been adopted by most states and some foreign countries. Test requirements have restricted the use of asphalts that harden excessively and those that have a high loss in ductility. Although limited data support the use of the TFOT to predict relative changes in asphalts during field-weathering, the test is used primarily to predict the relative changes in asphalts that occur during hot-plant mixing.

Oven Aging—Pauls and Welborn

In 1952, Pauls and Welborn reported the results of a laboratory study on hardening of asphalt (*27*). The data showed the effect of heat at 325 F (163 C) for various periods of time on the compressive strength of 2-in. x 2-in. (50-mm x 50-mm) cylindrical specimens of Ottawa sand asphalt mixes and the consistency of the asphalt recovered from the oven-aged specimens. Test data were obtained on asphalt cements representing major sources produced in the mid-1930s and included several cracked asphalts that were marketed at that time (*22, 23*). The study compared the properties of asphalts heated in the ⅛-in. (3-mm) TFOT at 325 F and asphalts recovered from the Ottawa sand mixtures after heating at 324 F. The following conclusions were made:

- Asphalt cements produced in the 1930s differed considerably in their resistance to hardening, depending on the source and method of refining.
- The hardening properties of asphalt cements can be determined either by measuring the compressive strength of laboratory oven-aged, molded specimens, by tests on the asphalt recovered from the laboratory-aged specimens or by the TFOT.
- Because the TFOT procedure is relatively simple, it is highly valuable for predicting high temperature hardening of asphalt cements.

Since the TFOT was first proposed, there has been criticism that the ⅛-in. (3-mm) film was too thick to relate to the hardening of thin films in asphalt paving mixtures. This prompted considerable research to develop microfilm aging tests.

Shell Microfilm Aging Test (Griffin, Miles and Penther)

Griffin, Miles, and Penther reported on the Shell microfilm test in 1955 (*28*). A 5-micron (0.0002-in.) film of asphalt was aged on glass plates for 2 hr at 225 F (107 C). The amount of hardening was determined by measuring the viscosity of the asphalt after aging and comparing it with the viscosity before aging. The durability was reported as an "aging index" (ratio of viscosity after aging to viscosity before). The report presented details of the apparatus, the aging-test method, and microviscometer. Tests were made on a number of asphalts, and the loss in weight and aging index were reported. No data were reported to show the correlation of laboratory-aging and field-aging. The study indicated that volatilization is important from the standpoint of hardening.

In 1958, the work by Griffin, Miles, and Penther was followed by a Heithaus and Johnson study that compared hardening of asphalt in a series of road test sections with hardening of asphalt in accelerated laboratory-aging tests (*29*). Eighteen asphalts covering different penetration grades and crude sources were used in short, experimental road test sections. It was found that correlation of laboratory- and field-hardening is improved when the field data are corrected to an initial void content of 10 percent. The study indicated that there is adequate justification for the use of the microfilm durability test to predict the hardening of asphalts in the field.

Hveem and Skog

Hveem and Skog proposed a modification of the Shell microfilm test that substituted a 20-micron (0.0008-in.) film of asphalt and exposed it to heat at 210 F (99 C) for 24 hours (*30*). The authors demonstrated indirectly that there was a relationship between field-hardening and hardening by their modified thin-film plate test.

Traxler

In 1961, Traxler reported a study comparing the hardening in the ⅛-in. (3-mm) TFOT at 325 F (163 C) for 5 hr with the hardening in a 15-micron (0.0006-in.) film thickness for 2 hr at 225 F (107 C) (*31*). Viscosities at 77 F (25 C) were determined before and after by the two methods for several aging periods. Tests on six asphalts used in the study showed that changes in the TFOT at 325 F were in the same order as those obtained by heating the 15-micron film at 225 F.

Halstead and Zenewitz

In 1961, Halstead and Zenewitz reported a study comparing the effects of aging by the ⅛-in. (3-mm) TFOT for 5 hr at 325 F (163 C) with an aging index from a microfilm test—15 micron (0.0006 in.) heated for 2 hr at 225 F (107 C) (*32*). Eleven typical 85-100 penetration asphalts were selected from those used in a previous study (*23*), which indicated that the hardening of asphalt in the TFOT is reported as percent of the original penetration. The hardening in the microfilm test is reported by an aging index, which is the ratio of the viscosity of the residue after aging for 2 hr at 225 F (197 C) to the viscosity before aging (*32*).

To obtain a direct comparison of the hardening by the two methods, viscosities in poises at 77 F (25 C) were determined on the original asphalts and the thin-film and microfilm residues, and aging indexes were calculated for both methods. All viscosities were calculated at a shear rate of 0.05 sec^{-1}. For low aging indexes (low hardening rate), there was no significant difference in the results of the two tests. As the resistance to hardening decreased, the increase in aging index for the microfilm residue increased much more rapidly than that for the TFOT residue.

In addition to comparing viscosities on the thin-film and microfilm residues, the authors showed that, for the asphalts included in the study, there was a straight line correlation between the aging index by the TFOT (⅛ in.—3 mm) and the percent of original penetration. The results of the TFOT could be evaluated on the basis of viscosity of the residues in poises obtained by the sliding plate viscometer. At that time, the authors pointed out the difficulties in the use of the sliding plate, its limitations for range in viscosity, and the sample preparation techniques that had to be used. The test has had only limited use as a specification test, but most of the difficulties have been eliminated by developing proper techniques.

Hveem and Skog California Rolling Thin-Film Oven Test (RTFO)

In 1963, in line with the effort to develop a test that would age the asphalt in a thinner film than the standard ⅛-in. (3-mm) TFOT, the California Division of Highways developed the RTFOT (*30*). A sample of asphalt cement (35 g ± 0.5 g) is placed in a bottle and exposed in an oven at 325 F (163 C) with a controlled amount of air circulated into the bottle during heating. The time of the test is 75 min, compared with 5-hr heating in the TFOT. Early laboratory test results showed a good correlation between viscosity on the residues from the standard TFOT and the RTFOT. A later study showed that the rolling thin-film residue viscosities correlated well with the viscosities of asphalts recovered from plant mixtures from eight field test sections in which a total of 24 asphalts were used (*30, 33*).

In 1963, the RTFOT was incorporated into a California specification as a tentative method. The test was adopted by ASTM in 1970 as the Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test) (D 2872). The test has been used to set limits for specification grades of asphalt cement based on the viscosity of the test residue at 140 F (60 C). Several of the Pacific Coast states have adopted the method and have used it to set grade limits based on the viscosity of the residue.

Skog subsequently presented a substantial amount of data that verified a correlation between the ⅛-in. (3-mm) thin-film oven test and the California rolling thin-film oven test (*30*). Both tests provide means for controlling changes in asphalt cements during hot-plant mixing.

Schmidt and Santucci Rolling Microfilm Test

Schmidt and Santucci proposed another microfilm durability test using the rolling thin-film oven (*34*). Essentially, a film of approximately 20 microns (0.0008 in.) is formed in the thin-film bottle by dissolving a specified amount of asphalt in benzene, coating the inside of the bottle, and evaporating the benzene during rotation of the bottle in the rolling thin-film oven. The microfilm is then exposed in the oven at 210 F (99 C) for 48 hr. During the aging period, the bottle is closed, but there is a small capillary tube through the stopper. After aging, the residue is removed for testing. The authors indicated that the test was easier to perform than the thin-film plate durability test proposed by Hveem and Skog and produced comparable results.

Rostler Ratio

The Rostler Ratio was derived to define the reactivity of the malthene fraction and is determined by dividing the sum of the most reactive components of the malthene fraction by the two least reactive components (*35*). It is a sulfuric acid precipitation method of chemical analysis developed by Rostler and Sternberg. The asphalt is separated into asphaltenes, nitrogen bases (N), first and second acidaffins (A_1 and A_2), and paraffins (P). Rostler and White developed test data showing a correlation between the Rostler Ratio and an abrasion test on Ottawa sand-asphalt mixtures. Later studies showed that viscosity of the asphalt significantly affected the abrasion results, but for comparisons made on asphalts with the same viscosity, the abrasion resistance decreased as the value of the parameter $(N + A_1)/(P + A_2)$ increased.

Heithaus Value "P"

The Heithaus test provides a method for studying the internal phase relationship of an asphalt (*36*). The test measures the peptizing power "P" of the malthene fraction P_o and the peptizability of the asphaltenes P_a. When the two factors are combined, the state of peptization "P" $= \left(\frac{P_o}{1 - P_a}\right)$ can be determined. The higher the value of "P," the more stable the internal phase of the asphalt system.

SPECIAL SPECIFICATION TESTS AND REQUIREMENTS

Beginning about 1930, the number of petroleum sources and asphalt product refineries increased rapidly. This initiated a concerted effort by consumer agencies to revise specifications to give more assurance of obtaining quality asphalts. A number of special tests and specifications requirements were devised to restrict the use of asphalt to certain sources of supply, usually the source an agency was accustomed to using. The tests and requirements generally were empirical and served only as identification tests. Otherwise the relationship of the property measured to pavement durability was indirect. Table 5 gives the results of a number of the special tests and proposed test requirements and the compliance or noncompliance of typical asphalt cements of the 50-60 and 85-100 penetration grades produced in 1935 (*22*). The asphalts represent production at that time. The table shows quite obviously that some of the requirements were so restrictive as to prevent the use of asphalts from almost all sources available at that time.

There were a total of 14 special tests and test requirements being used by one or more agencies. Some asphalts failed to meet 11 of the 14 requirements. The empirical nature of some of the tests is shown by the fact that one grade would fail to meet a requirement and the other grade from the same source would pass.

Currently there are other consistency and low-temperature ductility requirements being used in an attempt to control temperature and shear susceptibility and hardness at low temperatures. For example, one state requires that an AC-10 viscosity grade have a minimum ductility of 15 cm (5.9 in.) at 39.2 F (4 C) and 1 cm (0.39 in.) per minute and a minimum penetration of 80 at 77 F (25 C). Nationally the probability is good that more than 50 percent of the asphalts currently used in the U.S. would fail such a requirement. For 119 asphalt cements of 85-100 penetration grade produced in 1954-1956, 71 would not pass the 15 cm requirement. Ontario specifies 39.2 F (4 C) minimum requirements of 4, 6, 10, and 15 cm on 60-70, 85-100, 150-200, and 300-400 penetration grades respectively. These requirements are less restrictive than the one discussed previously. It is obvious from the above examples that extreme caution must be used so that asphalt supply in a marketing area is not unduly restricted.

CONTROLLED FIELD ROAD TESTS

Although numerous uncontrolled field-laboratory studies had been made and tests developed to determine the relative durability of asphalts, a link to tie asphalt properties to pavement performance and durability was still missing. The lack of performance data and the correlation with accelerated laboratory-aging tests became very important fac-

TABLE 5

50-60 AND 85-100 PENETRATION ASPHALTS THAT FAIL[1] TO MEET SPECIAL TEST REQUIREMENTS (22)

Special test	Fluidity factor		Float-test index		Pen. 39.2° F. / Pen. 77° F. (2)		Pen. 115° F.−Pen. 32° F. / Pen. 77° F. (2)		Ductility at 39.2° F., ¼ cm. per minute		Ductility at 32° F., ¼ cm. per minute				Ductility at 39.2° F., 5 cm. per minute		Toughness test		Organic matter insoluble in 86° B. naphtha		Fixed carbon		Sulphur		Film test		Oliensis test		Number of tests each sample fails to pass	
Proposed test requirement	140+		90+		30+ percent		4.2−		1/10 pen. at 77° F.		1/10 pen. at 77° F. −1		1/10 pen. at 77° F.		1/10 pen. at 77° F.		10+		15–29 percent		8–17 percent		3.0+ percent		Shall not coagulate		Shall show negative spot			
Penetration grade	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100	50 to 60	85 to 100
Sample number:																														
1	x	x	x	x	x	x	x	(3)			x		x		x	x	x		x	x	x	x	x	x					11	7
2	x	x	x		x		x				x		x		x	x	x		x	x	x	x	x	x					11	5
3	x	x	x		x	x	x				x		x		x	x	x		x	x	x	x	x	x					11	6
4	x	x	x		x	x	x				x		x		x	x	x		x	x	x	x	x	x					11	6
5	x	x	x			x	x				x		x	x	x	x	x		x	x			x	x				x	9	7
6	x	x	x				x						x		x	x		x		x			x	x					6	5
7							x								x														2	0
8	x	x					x				x	x	x	x	x	x			x								x	x	7	5
9							x								x	x			x										3	1
10							x								x	x													2	1
11													x		x	x													2	1
12															x	x													1	1
13	x	x											x		x	x								x			x	x	4	4
14	x	x	x				x						x		x	x								x					5	3
15	x	x	x				x						x		x	x											x	x	6	3
16	x	x	x										x		x	x								x			x	x	5	4
17	x	x	x				x								x	x								x					4	3
18			x				x								x	x													3	1
19		x	x				x				x		x	x	x	x		x										x	5	5
20		x							x		x	x	x	x	x	x			x										5	4
21		x					x				x		x		x	x	x												5	2
22		x									x		x		x	x													3	2
23	x	x	x			x	x		x		x	x	x	x	x	x							x	x	x	x	x	x	10	8
24		x							x	x	x	x	x	x	x		x						x	x					6	5
25		x	x				x				x	x	x	x	x	x	x	x		x			x	x					7	7
26	x	x	x				x				x		x	x	x	x							x	x			x	x	8	5
27	x	x	x			x	x						x		x	x				x			x	x					6	5
28		x	x			x	x				x		x		x	x		x					x	x			x	x	7	6
29		x				x						x		x		x		x						x		x		x		9
30		x	x									x	x	x	x	x							x	x					4	5
31		x							x		x	x	x	x	x	x			x										5	4
32	x	x	x				x				x	x	x	x	x	x							x	x					7	5
33	x	x	x				x			x	x	x	x	x	x	x							x	x	x	x	x	x	9	8
34	x	x									x	x	x	x	x	x											x	x	5	5
35	x	x	x				x				x		x		x	x							x	x					7	3
36	x	x	x				x			x		x	x	x	x	x							x	x			x	x	7	7
37		x											x	x	x	x								x			x		3	4
38		x										x	x	x	x	x							x	x			x		4	5
39	x	x	x			x	x		x		x	x	x	x	x	x	x										x	x	9	6
40	x	x	x				x				x		x		x	x			x				x	x	x	x	x	x	10	5
Number of samples failing each test	22	34	24	1	4	9	27		5	3	22	14	33	18	39	38	9	5	10	8	4	4	19	25	3	4	14	15		

[1] Samples marked (x) fail to meet requirement.
[2] Penetrations at various temperatures as follows:
32° F., 200 gm., 60 sec.
39.2° F., 200 gm., 60 sec.
77° F., 100 gm., 5 sec.
115° F., 50 gm., 5 sec.
[3] Penetrations not made at 115° F. on 85–100 penetration asphalts.

tors. Thus, from the 1950s to the present, more concentration has been given to implementing controlled field studies to determine the relationship of asphalt cement properties to pavement performance. The major field test road projects and their contribution to the problem are summarized in the following section of this synthesis.

Michigan Road Test

In 1952, Michigan conducted a study to determine whether the performance of the asphalts then being supplied differed from the performance of the asphalts that previously had been giving satisfactory service (*37*). The main differences in physical characteristics were in viscosity, temperature susceptibility, and stability to heat. These differences presented the following problems:

1. Lower mixing temperatures required by low-viscosity asphalts may result in inadequate drying of the aggregate. The problem had been encountered in some areas with certain mixture designs.
2. Effect of temperature susceptibility of asphalts on pavement performance in cold areas of Michigan—an asphalt with high temperature susceptibility might become excessively hard and brittle at low temperatures.
3. Low-viscosity asphalts having low temperature susceptibility may be more susceptible to bleeding and flushing under traffic in hot weather and may require a change in mixture design to prevent detrimental pavement behavior.

It also was observed in the laboratory that certain asphalts were permanently softened when heated to temperatures of more than 500 F (246 C).

Because of these problems and the lack of information about their effect on pavement performance, a controlled, field experimental project was planned and constructed in 1954. Six uniform test sections were constructed in which 60-70 penetration-grade asphalts from 6 Michigan sources were used.

A 4-year sampling and testing program and visual observation gave little or no evidence of differences in performance of the pavement sections containing the 6 asphalts (*38*). After 7 years, the ductility of the recovered asphalt from section 6 had dropped to 31 cm, and the others were more than 100 cm. Section 6 showed somewhat more pitting and cracking (*39*). After 12 years, no further difference in performance of the test sections was observed. However, a statistical analysis indicated a wider variation in asphalt properties obtained from sections 2 and 6 than the other 4 asphalts. Serafin, Kole, and Chritz indicated that asphalts in sections 2 and 6 changed more in service than the other asphalts (*40*).

One of the objectives of constructing the test road was to determine if any construction problems would arise from the use of asphalt sources that were becoming available in Michigan. No problems arose, and subsequent performance of the test road has provided justification for the use of asphalts from those sources.

In 1972, Corbett and Merz initiated a study of the asphalt cements used on the Michigan test road (*41*). The study was undertaken to (a) determine the extent of the change in chemical composition of the asphalt binders after 18 years of service; (b) relate the changes to the mechanism of binder hardening; and (c) relate, if possible, the compositional changes with respect to wear and weathering. Pavement cores were obtained from each of the six asphalt sections. The asphalt was extracted and was recovered by the Abson method for the top ⅛-in. (3-mm) layer and the next ¼-in. (6-mm) layer below the saw cut. Compositional analysis by the Corbett method, together with the physical properties of both the original and recovered binders, led to the following observations:

- In all cases, the viscosities at 140 F (60 C) and softening points increased and the penetrations and ductilities decreased. The changes were greater in the binder from the top ⅛-in. (3-mm) layer than in the binder from the ¼-in. (6-mm) layer below it. The binders from sections 2 and 6 had the highest viscosities and the lowest ductilities.
- The saturate content from recovered binders was virtually unchanged from that of the original binders. Slightly greater differences usually were found in the top layer.
- The amount of naphthene aromatics decreased in all sections similar to that reported for asphalts that are air-

TABLE 6

PHYSICAL PROPERTIES OF ORIGINAL AND RECOVERED SAMPLES (*41*)

Sample	Property	Section 1	2	3	4	5	6
Original	Softening point, deg F	126	124	124	125	125	126
	Penetration at 77 F	46	52	48	49	51	49
	Ductility at 60 F, cm	150+	150+	150+	67	16	27
	Viscosity at 140 F*, poises	3,880	5,310	3,290	4,480	6,410	7,740
Recovered, top ⅛-in.	Softening point, deg F	136	150	140	147	147	165
	Penetration at 77 F	26	19	23	23	23	19
	Ductility at 77 F, cm	150+	7	150+	6	7	5
	Ductility at 60 F, cm	5	0.5	4.5	—	3	2.5
Recovered, ¼-in. minus	Softening point, deg F	129	136	133	135	138	147
	Penetration at 77 F	37	34	36	35	36	32
	Ductility at 77 F, cm	150+	150+	150+	150+	150+	40
	Ductility at 60 F, cm	8	8.5	8.5	6.5	6	4.5
	Absolute viscosity at 140 F, poises	7,320	17,041	7,752	9,705	11,787	34,414

Note: 1 in. = 25 mm; 1 F = 1.8 C + 32; 1 poise = 0.1 Pa·s.
*1965 data.

blown. Asphaltenes consistently increased, especially in the top layer. Polar aromatics showed no distinct pattern.

The physical properties of the original and recovered asphalts are given in Table 6. The mechanism of change in chemical composition is shown in Figure 3.

A visual system was used to rate the sections. Sections 2 and 6 showed more wear and raveling than the other sections, and the recovered asphalts from these sections showed the greatest changes in physical and compositional properties. The authors concluded that, considering the age of the road and the current level of hardness of the binder, no gross distinction could be made among the binders included in the study.

In 1977, ASTM published a proposed test method based on the work of Corbett and Merz (*42*).

Zaca-Wigmore Test Road

The Zaca-Wigmore test road constructed in California in 1954 is one of the best illustrations of the relationship of asphalt cement properties to pavement durability. The final report was published in 1969 (*43*). Asphalts of 200-300 penetration were used and, with the exception of an asphalt from Arkansas, they represented California crude sources. Most of the asphalts were used in 2500-ft (760-m) sections in new alignment and as an overlay on an existing concrete pavement. The test sections were constructed under nearly identical conditions.

Detailed studies were made of the mixtures at the time of construction. Performance ratings were made on the test sections, and laboratory studies were made on samples from each of the test sections at several intervals during approximately nine years of service. Numerous routine and research tests were made on the original asphalts and on asphalts recovered from pavement samples. These were the major findings of the study:

- The criterion for performance was set at 10 percent of the surface showing fatigue "alligator" cracking in the travel lane. One asphalt section developed this amount of cracking in 38 months of service. During the life of the study, other forms of distress noted were raveling, block cracking, transverse cracking, and longitudinal cracking.
- An excellent correlation was found for the hardening of the asphalts during plant mixing and during the standard thin-film oven test..
- The rate of hardening under equivalent weathering and pavement conditions was influenced by the source of the asphalt. The hardening can be attributed mainly to the initial void content and rate of change in void contents during pavement life.
- Ten test sections showed some degree of failure between 38 and 92 months of service. Seven sections remained in satisfactory condition after nine years; most of these were sections on old concrete.
- The amount of fatigue cracking appeared to be related to the consistency of the recovered asphalt as measured by penetration or viscosity. Other forms of cracking appeared to be related to the gain in sheer susceptibility of the asphalt during service life. This also was indicated by loss of ductility.

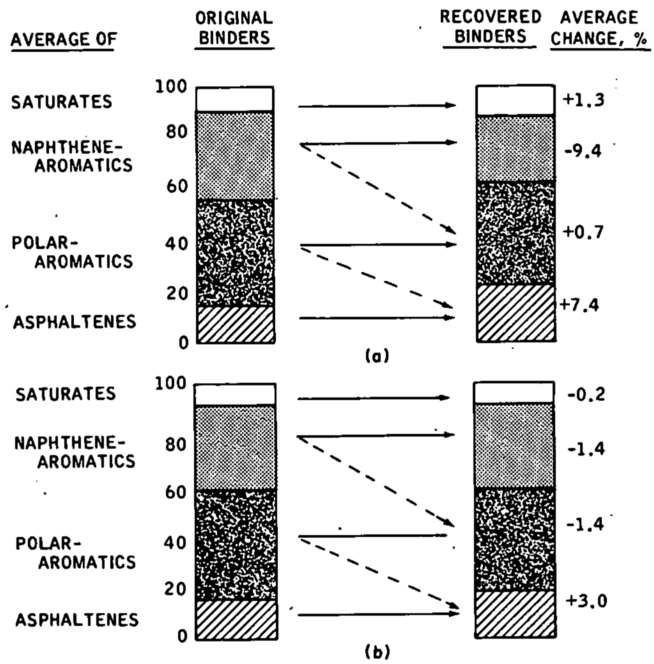

Figure 3. Mechanism of change for (a) ⅛-in. layer and (b) next ¼-in. layer (41).

- The durability of the asphalt in service appears to be predicted best by the Shell Modified Test (*44*).

It should be noted that those asphalts resulting in early pavement distress would not meet the present AASHTO specifications for penetration-grade asphalt. They were high in loss in the thin-film oven test, and the residue was low in percent of retained penetration. One asphalt was low in ductility.

Davis and Petersen used inverse gas liquid chromatography (IGLC) to study the asphalts from the Zaca-Wigmore test road (*45*). The principle of the IGLC technique is to measure the retention behavior of selected test compounds that possess different functional groups in the IGLC column. To study oxidation characteristics, the asphalt is oxidized in the IGLC column to determine the retention behavior of the test compounds on the oxidized asphalt. Retention behavior is a measure related to the chemical composition of the asphalt.

Studies were made to determine the relationship between the IGLC test results on the weathered asphalts and their performance in road service and the changes in the asphalts during the laboratory microfilm durability test. A good correlation was found between road surface performance and the interaction coefficient (I_p). Figure 4 shows the correlation with phenol. The phenol I_p also correlated with the viscosity changes as measured by the microfilm durability test (aging index). As indicated earlier, aging index is the ratio of viscosity after oxidation to the viscosity before.

Road Tests in France, Germany

Eight 70-100 penetration asphalt cements differing in physical characteristics were used in experimental pave-

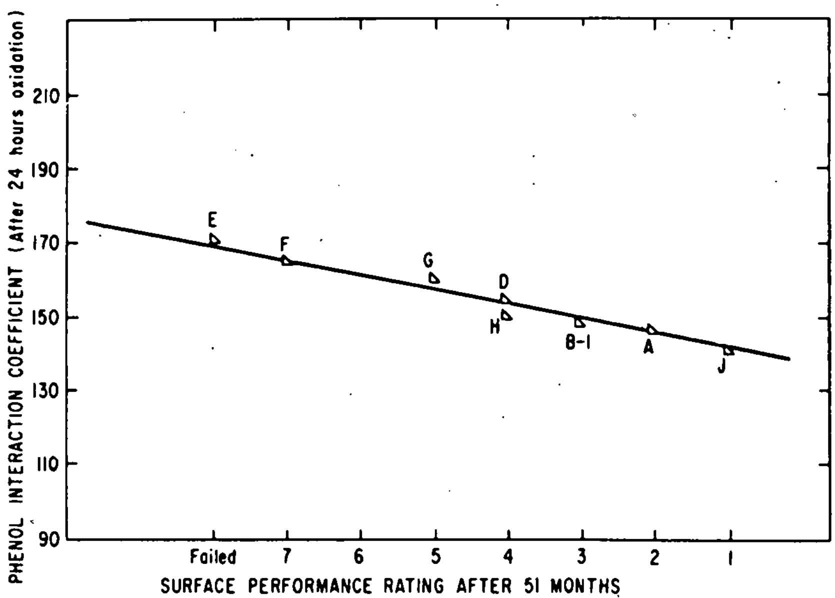

Figure 4. Surface performance rating after 51 months (45).

ments constructed in France in 1963 (RN7) and Germany in 1964 (B2) (*46, 47*). Two mixture designs, two aggregates, and three binder contents for each asphalt were investigated in each road trial. For each trial, 110 test sections were constructed, including 14 control sections using one asphalt to establish variability during construction. The reports cover, for each road trial, details of the properties of materials used, mixture designs, construction methods, methods of assessing pavement conditions, and pavement performance. Chemical and rheological properties of the bitumens recovered after 20 months of the RN7 road trial were reported.

Visual inspections and deflection and skid-resistance measurements were made after five and six years of service for the B2 and RN7 road trials. There were slight deformations on a number of sections. Laboratory studies were made to determine changes in chemical composition and physical properties of the aged asphalts and to compare the results with the effects of laboratory-aging techniques.

Despite differences in the initial characteristics of the asphalts, no large differences in pavement performance attributable to the asphalts were found. The differences observed in the various test sections after five and six years were accounted for by differences in aggregate gradings and defects in the road structure. The authors anticipated that if the performance of the road trials proceeded in the same manner, differences in the effect of the properties of the different asphalts would be shown.

In France, an inspection and measurements were made in 1974 after 11 years of service. Over-all, serviceability was still good, although on one side of the road there was a fair amount of longitudinal cracking, which appeared to have been caused by pipe-trenching beside the road. Bitumen recovered from the upper 3 mm (⅛ in.) of core specimens showed only minor changes in chemical composition with time. The fact that all test sections were in sound condition after 11 years under heavy traffic in a warm climate is probably due to the dense, impermeable nature of the asphalt surfacing, which prevents deterioration of the binders. The study has been cut back severely but will continue, and a final report summarizing all information is planned.

In Germany, the large-scale trial was terminated in 1971. The wearing course had suffered such severe damage from studded tires that the local authority had no alternative but to resurface the road. The data obtained in 1970 and 1971 did not necessitate any modifications in the conclusions based on 1969 data.

Iowa Road Test

Eight asphalt pavements selected by the Iowa State Highway Commission were the basis of a study of changes in rheological and chemical properties after service for 48 months (*48*). The pavements were constructed during the late 1967 and early 1968 construction seasons. Samples of asphalts, mixtures, and pavement slab or cores were obtained at the time of construction. Sets of cores or slab samples were taken from the wheel paths and from between the wheel paths at six-month intervals up to 48 months of service for each pavement.

The eight asphalt cements represented four sources. They were analyzed for penetration at 77 F (25 C), viscosity at 77 F and 140 F (60 C), microductility, and softening point. They also were subject to the TFOT, the Iowa Durability Test (IDT), and chemical analysis by the Rostler method. Infrared spectra were obtained through the use of multiple internal reflection techniques.

In the IDT, the residue from the ⅛-in. (3-mm) TFOT was exposed to a pressure-oxygen treatment of 20 atm (2000 kPa) oxygen at 150 F (66 C) for up to 1000 hr. Changes in physical and chemical properties of the asphalt were determined for the recovered asphalts after six-month intervals of service in the road and for the asphalts after 24, 48, 96, 240, 480, and 1000 hr of exposure in the IDT.

Two conclusions of the study are of interest here. First, good correlations between field-service aging and laboratory aging during the IDT were indicated. The master time-equivalency curve between the IDT in hours and pavement life in months, established by combining all asphalts at equivalent void levels and properties, indicated that 46 hr in the IDT would age asphalts to the equivalent of 60 months of service. Second, except for some transverse and centerline cracks, all the pavements were in good condition.

Delaware Road Test

Kenis reported on experimental test sections constructed in Delaware in 1958 (*49*). Two sources of 60-70 penetration asphalt cement were used in dense-graded asphaltic concrete mixtures as overlays on rigid and flexible bases. The Asphalt Institute and the Bureau of Public Roads participated in the project, and representative samples of the mixtures at the time of construction and after two years were tested by three laboratories. Kenis made the following observation concerning the results of tests on the recovered asphalt: "At present no specific conclusion can be drawn, but the laboratory tests indicate that variances in results of tests on the same asphalt at different sample locations in the road may be as great or greater than variances in the asphalts from the different crude sources used in this study."

After publication of the report, study was continued to 103 months, at which time the pavements were still performing satisfactorily. The recovered asphalts were tested by the Bureau of Public Roads after 103 months. The results, which tend to support Kenis' statement, are as follows:

Asphalt	Penetration 77 F (25 C) Avg.	Range	Ductility 77 F (25 C) Avg.	Range
A	20	17-22	15	9-27
B	21	20-24	12	8-19

Virginia Test Road

Virginia conducted a study similar to the Delaware study but with three asphalts. At 7½ years service, no distress was noted. No report has been published.

Federal Highway Administration

The Federal Highway Administration (FHWA) made a comprehensive study of asphalts and the performance of pavements in which they were used (50). The study was the culmination of work that began in 1954-1956, when asphalts representing current production in the U.S. were collected and analyzed. The asphalts represented those used in 285 identifiable construction projects in 37 states.

In 1967, a study was initiated to survey the pavements where the known asphalts were used and to sample a preselected number of in-service and out-of-service pavements. The objectives of the study were to determine the over-all changes in the fundamental physical and chemical properties of the recovered asphalts after 11 to 13 years of service, to relate the changes to the fundamental properties of the asphalts before and after laboratory aging, and to relate the changes to pavement performance.

To accomplish this objective, 53 pavements in 19 states were selected for study. A two-man rating team visually examined and rated each pavement for such distresses as cracking, raveling, and instability. The rating team selected the sampling location, within which five or six random sampling sites usually were identified. All sampling was done by the states, and the samples were shipped to the Materials Division of FHWA, where fundamental and conventional tests were performed on the mixtures and recovered asphalts. Chemical analysis by the Rostler method was performed by Materials R & D, which also assisted in the data analysis and report writing. All data were stored on computer cards.

Following are the major findings:

- There was no over-all correlation between the properties of the original and recovered asphalts and the performance of the pavements.
- Limited data showed that loss of matrix was more severe with high viscosity asphalts and higher traffic volumes.
- Numerous correlations or trends were shown between changes in chemical and physical properties.

Zenewitz and Welborn made detailed computerized linear regression analyses of the data (*51*). Included were linear regression equations, analysis of variance, coefficient of correlation, and standard error. Rostler's analysis was used to relate penetration and viscosity of original asphalts, thin-film residues, and recovered asphalts to the void contents of pavement samples and to chemical fractions. Coefficients of correlation ranged from —0.84 to —0.93. The more important findings are as follows:

- The consistency of the thin-film residue provided a better reference point than did the consistency of the original asphalt.
- Of the chemical fractions, the second-acidaffin and paraffin content (P) of the original asphalt related best to the ultimate hardening level of the asphalt after service. The higher amounts of each of these fractions were associated with a lesser degree of hardening, assuming all other factors were constant.
- Regression analysis also showed that relatively high content of first acidaffins (A_1) correlated with greater hardening of the binder.
- Long-term hardening in the pavement generally can be estimated from a knowledge of the asphalt content and volume of air voids.
- The data from this study are available for studying the effect of temperature and shear susceptibility on pavement performance.

A study of the variability of the properties of the pavement samples within and between projects indicated the following:

- Pavements should be sampled at several random sites so that meaningful estimates of mixture and asphalt properties can be obtained.
- Significantly lower sampling and testing variability of the bulk specific gravity measurements were obtained in 8-in. (200-mm) core samples than in 6-in. (150-mm) and 4-in. (100-mm) samples. Whenever possible, 8-in. cores should be used.
- Based on the findings of this study, the authors recommend that average mixture and pavement properties should include standard deviations and coefficients of variation.

Although not included in this synthesis, several correlations of variability were made on properties of pavement and mixture samples from surviving and nonsurviving pavements.

STUDIES OF FUNDAMENTAL PROPERTIES OF ASPHALT

In the early 1960s, serious consideration was given to the development of test methods and information on the fundamental properties of asphalt. Because consistency was believed to be of primary importance, the research effort was directed to the development of tests that would measure viscosity in fundamental units and would determine the relation of these fundamental tests to mixture design, behavior during construction, and pavement performance (*52*).

As part of a national effort, FHWA implemented a comprehensive research program to develop and standardize fundamental test methods and to develop fundamental knowledge for defining the essential functional properties of asphalts (*53*). Favorable information was to be related to the states and to national specification writing groups. Continued research on the problem was supported by Transportation Research Board Committee A2D05, General Asphalt Problems, and by the Asphalt Institute, AASHTO, and ASTM. Committee A2D05 recommended that methods be developed for determining viscosity over the entire temperature range of interest in asphalt construction, with special emphasis on measurements of consistency at low temperatures. The states, industry, universities, and other groups showed considerable interest in developing a coordinated program.

During the 1960s, methods for measuring viscosity in fundamental units over a temperature range of 32 F (0 C) or lower to 325 F (163 C) were developed. Kinematic and absolute viscosity tests now are widely used in specifications for cutbacks and asphalt cements.

As part of the national program, FHWA encouraged the construction of road trials that would include requirements for fundamental measurements and for evaluating the performance of asphalt during construction and after aging in the pavement. Some of the major research programs and contributors to the over-all effort are described in the following sections.

Viscoelastic Properties Studied by Sisco and Brunstrum

Many studies have shown the changes in asphalt consistency with aging. Measurement of aging by viscoelastic properties had been neglected because of the lack of good, commercially available equipment to make complex viscoelastic measurements. The effect of aging is best evaluated when laboratory measurements can be related to performance under a wide range of stresses.

A Weissenberg rheogoniometer, modified to improve temperature control and accuracy of strain measurements, was used on retained unaged and aged asphalts from 1954-1955 pavements that had been in service for about 11 years and on residues from the TFOT (*54*). The frequency of stress application ranged from 4×10^{-7} to 10^2 cycles/sec, and the test temperature range from 0 to 80 F (−18 to 27 C). Viscoelastic and other tests also were made on a series of viscosity-graded asphalts that covered the range of rheological types available in the U.S. in 1964. Marshall stability specimens containing these asphalts were aged outdoors for 345, 737, and 1230 days. The viscoelastic properties were determined for recovered asphalts from the pavement samples and Marshall specimens and for the residues from the TFOT. Asphalt composition by a combined solubility and chromatographic procedure, molecular weights, and glass transition measurements also were reported for selected asphalts.

Following are the study results that concern the relation of asphalt cement properties to pavement performance:

- Large increases, induced by aging, in the hardness of the asphalt binder (as measured by complex modulus) are associated with road-cracking.
- The large differences in viscoelastic properties that can develop during road-aging are due partly to intrinsic differences in aging resistance and partly to external factors.
- The age-hardening of asphalts in the road does not correlate directly with the amount the asphalts hardened in the TFOT.
- The rheogoniometer, when modified to control temperature and improve the strain transducer, provides an accurate and convenient instrument to measure the load response properties of asphalt cements.

Pennsylvania

In 1968, Sandvig and Kofalt described three series of experimental road trials in Pennsylvania. The roads contained six or seven asphalts from different sources and varying in penetration and viscosity (*55*). The aggregates and mixture designs differed for each series. Penetrations of the asphalts ranged from about 60 to 150, and viscosities at 140 F (60 C) ranged from about 966 to 3198 poises (97 to 320 pascal-seconds). During construction of the test sections in each project, mixture and construction variables were maintained as uniformly as possible. Mixing temperatures were controlled by viscosity, which varied between approximately 140 and 300 centistokes (140 and 300×10^{-6} m²/s). All the asphalts hardened but in varying amounts during mixing. For two of the projects there was a good rank correlation between the penetration of the thin-film residues and the penetration of the recovered asphalts. Except for one asphalt, there also was a good rank correlation between the viscosity of the thin-film residues at 140 F (60 C) and the viscosity of asphalts recovered from the mixtures immediately after plant mixing. These correlations verify those developed by others. After about

20 months' service, the sections having different asphalts in two road trial series showed only minor differences in performance; one section and part of another showed some differences in surface texture after 30 months.

Shear susceptibility (or shear index), as emphasized in the Pennsylvania study, is the tangent of the angle of log shear rate (X axis) versus log viscosity (Y axis) determined from viscosity measurements using the microviscometer (*56*). Shear susceptibility values were determined on six asphalts recovered from the test pavements at several periods up to 78 months.

Aging indexes also were calculated, based on changes in the viscosity of the asphalt at 77 F (25 C) (shear rates of 0.05 and 0.001 sec^{-1}) and at 140 F (60 C). For the six asphalts, only the aging indexes based on viscosity at 77 F (25 C) (0.05 sec^{-1}) conform with pavement performance (*56*).

The over-all ratings after 80 months of service, based on riding quality, raveling, loss of matrix, rutting, cracking (shrinkage), and surface texture, were as follows (*56*):

Asphalt No.	Rating
1	19 (poorest)
2	22
6	23
4	25
3	29½
5	31 (best)

Asphalt No. 1 showed raveling after 24 months' service. However, the test section was not adequately compacted and maintained a higher void content than the sections where the other asphalts were used.

The authors also indicated that a rank correlation was obtained on aging indexes and shear susceptibility and that control of the gains in shear susceptibility and aging index is a necessary specification requirement. A shear susceptibility requirement on the thin-film residue can be substituted for a ductility requirement. Also, a maximum aging index based on viscosity at 77 F (25 C) on the thin-film residue should be incorporated in specifications for paving asphalts.

In discussing the Pennsylvania study, Fabb indicated that control of the increase in shear susceptibility as a specification requirement was not acceptable at the present time (*57*). Mixture design, initial binder consistency, and air voids would greatly affect the performance of the six asphalts. However, consistency and shear susceptibility can be correlated with pavement performance. For the Pennsylvania study, these factors are greatly associated with the hardening effects caused by void contents. Fabb thus indicates again that hardening susceptibility due to mixture properties such as voids is an overriding factor in judging the bitumen characteristics and their relation to pavement performance.

Fabb (*57*) mentioned another road trial in Belgium that showed a relationship between shear susceptibility and skid resistance for six asphalts. The skid resistance was measured at 50 and 80 km/h (30 and 50 mph) by the sideways force method after 4 years of service. Shear susceptibility was expressed in terms of n_1/n_2, where

n_1 = apparent viscosity at 25 C (77 F) and shear stress of 10^4 dynes/cm^2 (1 kPa)

n_2 = apparent viscosity at 25 C (77 F) and shear stress of 3×10^5 dynes/cm^2 (30 kPa)

Fabb concluded that, for the Belgium study, high shear susceptibility was associated with improved skid resistance, particularly at higher speeds. Furthermore, he noted that higher shear susceptibility is associated with lower increase in stiffness with temperature and loading time.

In 1975, Kandhal and Wenger reported on the performance of 6 test pavements in Pennsylvania (*58*). The primary variable was the characteristics of the asphalt. Condition evaluations made after 80 and 113 months included riding quality, raveling, spalling, loss of matrix, rutting, cracking (transverse and longitudinal), and surface texture. Eight evaluators were used for pavement condition survey after 113 months.

A perfect performance rating would be 72. The average over-all ratings obtained by the 8 evaluators on individual pavements are given in Table 7, which also summarizes the relation of asphalt cement properties to pavement performance.

The slope of the relationship of shear susceptibility and viscosity proved a better correlation with pavement performance than either shear susceptibility or viscosity alone. Asphalt No. 1 consistently was rated the poorest in performance and physical properties during service. Raveling was first observed after 30 months. The authors believed this was due to the high viscosity, which prevented maximum compaction. This is reflected in a void content of more than 5 percent for asphalt No. 1, compared with a range in voids of 3.0 to 4.7 percent for the other asphalts.

California

From 1964 to 1969, the California Division of Highways constructed 8 series of road tests in which 24 asphalt cements were used (*59*). The first objective of the road tests

TABLE 7

RELATION OF PAVEMENT PERFORMANCE TO PROPERTIES OF RECOVERED ASPHALT (PENNSYLVANIA) (AFTER *58*)

Test Pavement	Performance Rating	Viscosity 77 F (25 C) 0.05 sec^{-1} Rating	Shear Susceptibility Rating	Slope m′ of Shear-Viscosity Curves at 77F (25 C)	Ductility 39.2 F, 1 cm/min Original Asphalt (cm)	Ductility 39.2 F, 1 cm/min After Mixing (cm)	Ductility 60 F 5 cm/min (cm)
1 (poorest)	51.1	1	1	1.174	14	4.1	0
6	59.8	6	4	1.354	21.9	7.3	8
4	60.1	5	6	1.431	23.5	7.5	7
2	60.4	4	5	1.738	53.3	11.9	19
5	61.2	2	3	2.859	68.3	24.3	19
3 (best)	61.5	3	2	3.166	101.0	42.2	49

Note: Tests are on asphalt recovered after 113 months of service.

was to evaluate the asphalts' ability to meet a new, tentative specification based on viscosity grading of the residue from the rolling thin-film oven test, which was designed to control uniformity, "setting" during construction, and asphalt durability. The second objective was to determine the correlation of several laboratory durability test methods with the durability of the asphalts in service.

To determine the effect of the environment, the series of road tests were located in various climatic areas of the state. In each test series, at least one special asphalt manufactured to meet the proposed tentative specification was placed and evaluated along with the job asphalt.

Many studies have shown that the change in consistency with age is a means of evaluating durability. The viscosity of the asphalts recovered from samples of the various test sections after 30 and 50 months in service was correlated with the viscosity of residues from the following laboratory aging tests:

- California weathering plate test—210 F (99 C), 24 hr
- Extended rolling thin-film oven test—325 F (163 C), 5 hr
- Chevron rolling microfilm test—210 F (99 C), 48 hr
- Ottawa sand mix weathering test—140 F(60 C), 400 and 1000 hr
- Field density briquette (lab molded)—140 F (60 C), 90 days

The Rostler Ratio $(N + A_1)/(P + A_2)$, the Heithaus "P" value, and the initial void content of pavement samples also were determined.

Two statistical methods of analysis were used to determine how field viscosities after 30 and 50 months of service correlated with the various laboratory procedures listed previously. The statistical methods follow.

Least Squares Regression Analysis

A linear transformation of the power function $Y = Ax^b$ and the exponential function $Y = Ae^{bx}$ was used to determine the better regression. The power function was used when viscosities of residues from aging tests were plotted against viscosities of recovered asphalts, and the exponential function was used when field viscosity was plotted against a linear number such as voids, Rostler Ratio, and Heithaus "P." All the data were correlated on the basis that all test sections together represented a single section (Fig. 5).

Covariance

In this system, the individual correlations of the test sections are compared on the basis of a common slope (Fig. 6). This analysis tends to negate individual differences of the separate test sections, such as differences in voids, asphalt content, and environment.

Following are most of the findings and conclusions to date:

- The asphalts graded on the basis of rolling thin-film oven residue had excellent "setting" properties.
- The superior qualities of the experimental asphalts used on the Willits section appear to be a combination of moderately low voids and good asphalt durability properties.
- At comparable void contents, weathering of the special asphalts was not significantly different from weathering of the control asphalts.
- Original void content is a definite factor in long-term asphalt durability.

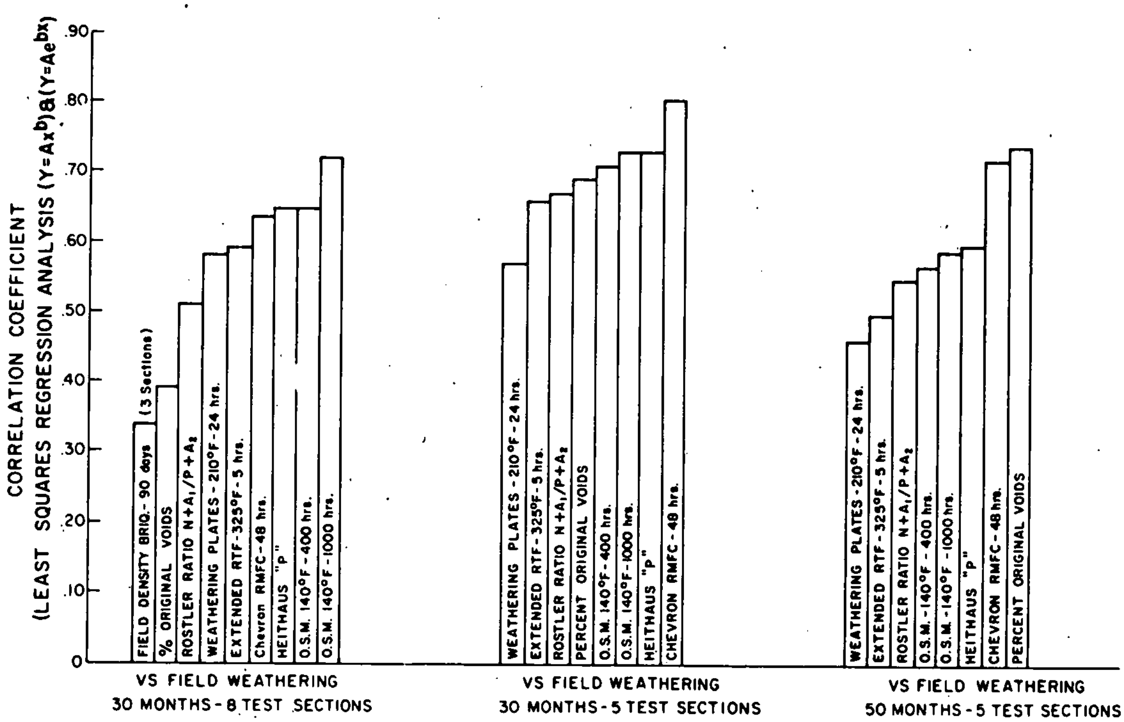

Figure 5. Comparison of correlation coefficients (least squares regression analysis) (59).

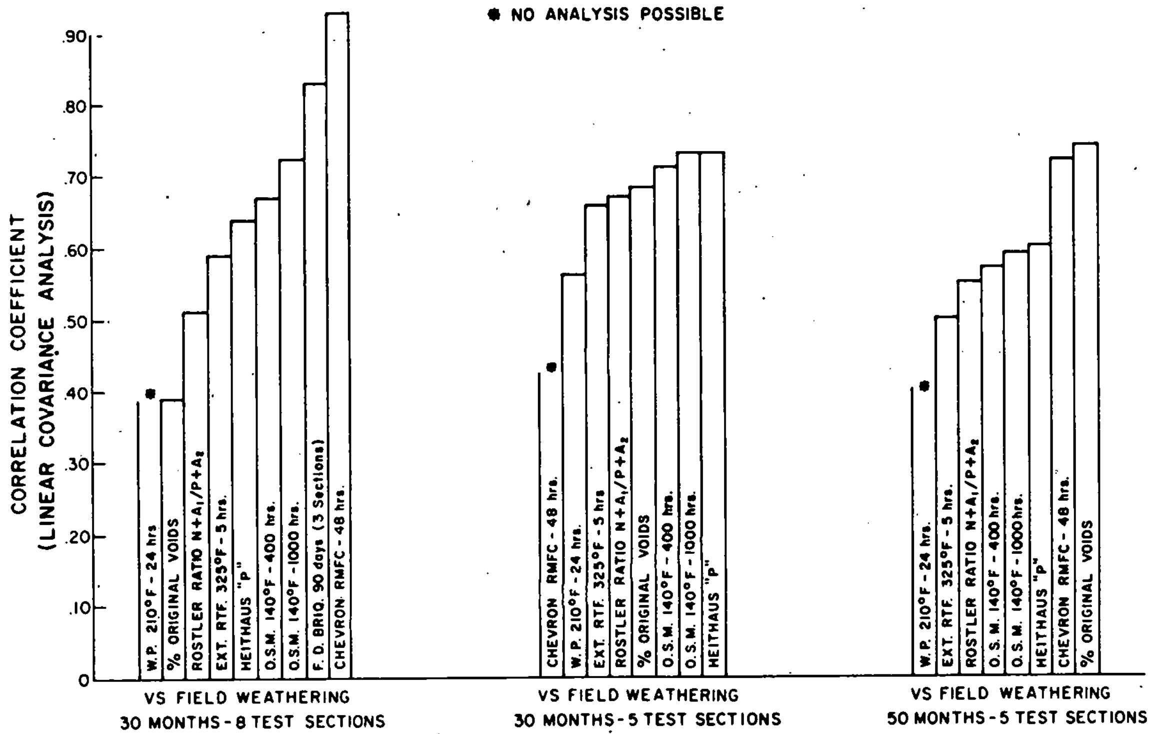

Figure 6. Comparison of correlation coefficients (linear covariance analysis) (59).

• The poorest correlation with field-weathering was obtained with the weathering plate test. The best correlation appeared to be obtained with the Chevron rolling microfilm test at 48 hr.

• More field-weathering is needed before final conclusions can be made on test methods that will predict durability.

Later inspections were made at periods of service from 48 to 108 months for the various test roads (*60*). The following findings and conclusions were reported:

• With respect to durability, the specially manufactured asphalts have not performed significantly different than their respective control asphalts.

• The differences in the test sections were caused by design, construction, and weathering factors.

• During the construction process, none of the tentative specification asphalts caused any significant problem.

• During rolling, the variability of asphalt viscosity, which is related to "setting," can be controlled by grading the asphalt after an oven heat treatment test (RTFOT).

• As indicated for earlier service periods, none of the laboratory test procedures evaluated in this study as predictors of asphalt durability correlate well enough with field hardening to use as a specification requirement. The lack of correlation may have been due to uncontrolled variables.

• The development and adoption of a viscosity-graded specification for paving asphalt cements by the State of California are the results of the pavement asphalt study.

Utah

Utah evaluated the relationship of asphalt properties to field performance (*61*). The study included 20 controlled test sections where design, environmental factors, and construction were essentially the same. Also included were 108 uncontrolled sections that were evaluated subjectively. Of these, 39 also were evaluated objectively. The subjective rating included a 1-to-5 rating of transverse, longitudinal, and map cracking; bleeding; polishing; rutting; spalling; and roughness. A rating of 1 indicated severe distress, and a rating of 5 indicated no distress. The objective survey included actual measurements of the number of transverse cracks, metres of longitudinal cracks, square metres of map cracking, rutting, and surface roughness as measured by a PCA roadmeter.

The report deals with a group of asphalt cements from eight sources. The group includes viscosity grades of AC-5, 10, 15, 20, and 40. Objective evaluations were made to compare transverse cracking with (a) the properties of the original asphalt, (b) the properties of the asphalt after the rolling thin-film oven test, and (c) the properties of the asphalt recovered from the pavement sections.

Correlations were made with the average transverse cracking and asphalt properties. Transverse cracking ranged from 0 to 59 cracks per kilometre (0 to 95 per mile).

Fair to good correlations were found for transverse cracking and:

1. Aging index (ratio of field viscosity to original viscosity).

2. Cannon cone viscosity at 25 C (77 F) on field asphalts.
3. Ductility at 4 C (39.2 F) on field asphalts.
4. Forced ductility—tensile force required to elongate ductility specimen at 4 C (39.2 F), 1 cm/min on original asphalts.
5. Temperature susceptibility in the 25-60 C (77-140 F) range on original asphalts.
6. Based on Rostler's method of analysis, paraffin contents of original and field asphalts relate closely to stiffness and cracking. High paraffin contents (20-25 percent) were indicative of more cracking than lower contents (9-13 percent).

The authors concluded that the source of the crude is the major variable affecting performance of asphalts in Utah.

For the controlled test sections, the following correlations were found:

- A general relationship was found between the age of the pavement and observed cracking.
- The most apparent variable associated with cracking was the asphalt source.
- The following correlation coefficients were determined:

(a) Cannon cone viscosity at 25 C (77 F) vs. penetration at 25 C (77 F): R = 0.94 (at 0.1 percent level)
(b) Cannon cone viscosity at 4 C (39.2 F) vs. ductility at 4 C (39.2 F) on field samples: R = 0.76 (0.1 percent level)
(c) Aging index vs. force ductility field samples: R = 0.73 (0.1 percent level)
(d) Temperature susceptibility vs. paraffin content of original asphalts: R = 0.84 (0.1 percent level)

Washington

Le Clerc and Walter reported on a limited study concerned with the performance of asphalt used in the base, leveling, and surface courses of four pavements in Washington (*62*). After six years of service, one pavement developed extensive wheel path cracking, two pavements developed slight cracking, and the other pavement showed no cracking.

Void contents and extraction and recovery tests were made on each of the three layers. Penetration at 77 F (25 C) and ductility at 45 F (7 C), 1 cm/min, were determined on the recovered asphalt. The pavements were rated according to the Washington method. The pavement that was rated lowest (40) had extensive longitudinal cracking in the wheel paths and some transverse cracking. Two of the pavements, one rated at 52 and the other at 59, had some wheel path cracking. The other pavement was rated at 62 and showed no distress. The ratings and tests on the recovered asphalts are given in Table 8.

The relationship between penetration at 77 F (25 C) and ductility at 45 F (7 C) is shown in Figure 7. The data again support the fact that, if ductility is to be considered an indication of asphalt performance, the penetration or consistency must be known so that a proper evaluation can be made.

TABLE 8

PAVEMENT RATINGS COMPARED TO PROPERTIES OF RECOVERED ASPHALT (WASHINGTON) (*62*)

Project Number	Rating	Penetration, 77 F (25 C)			Ductility, 45 F (7 C) 1 cm/min		
		Wearing	Leveling	Base	Wearing	Leveling	Base
8086	40 (very poor)	18	22	24	1-	1.5	2.5
8101	52 (poor)	12	22	49	1-	5	51
8200	59 (fair)	15	35	46	1-	11	72
8138	62 (good)	24	50	48	5.5	100+	100+

Louisiana

The Louisiana study had three objectives (*63*). First, data were sought on changes in the physical characteristics of penetration-graded and viscosity-graded asphalts with time in service. Second, the influence of the changes in asphalt characteristics on durability (performance) of the asphalt concrete pavements were examined. Third, the physical properties of the mixture, specifically air voids, were related to the rate of hardening of the various asphalt cements.

The asphalt cements used in the study included six viscosity-graded asphalts from four sources and four penetration-graded asphalts from the same sources. For the viscosity-graded asphalts, the penetrations ranged from 34 to 81. The penetration-graded asphalts ranged from 54 to 66.

The test sections were constructed as overlays on a 5-mile (8-km) length of 6-in. (150-mm) thick portland cement concrete pavement. The existing pavement was widened and overlaid with 2 in. (50 mm) of binder course and 1.5 in. (38 mm) of wearing course. Approximately 90 ft (30 m) of sampling sites were randomly selected for each asphalt. Four 12-in. (300-mm) samples were obtained from the outside wheel path for each site after 1, 36, and 110 days and after 1, 3, and 5 years. At each sampling period, pavement performance evaluations were based on visual rating, Mays ridemeter, longitudinal wheel path rutting, cracking, raveling, and loss of matrix. Samples of the surface course were extracted and recovered by the Abson method. The Asphalt Institute tested duplicate pavement samples by using benzene solvent and centrifuge extraction. Louisiana used the reflux extractor with trichloroethylene solvent.

A cursory inspection of the test data revealed marked differences between the two laboratories in the measured characteristics. The differences were attributed to different methods of sample preparation and extraction and to the solvent used for extraction. The author indicated that the ASTM methods for extraction and recovery were not adequate.

In spite of the variations in test data, a method of analysis developed by Brown et al. was used to correlate the rate of change in the properties of asphalt during service (*64*). Based on the limiting change criteria for penetration, all viscosity-graded asphalts were rated more durable than penetration-graded asphalt cements; however, the penetrations of four of the original viscosity-graded materials were lower than the penetration graded materials from the same source.

A plot of the aging index versus time in service can be used as an indicator of relative durability. A flat slope implies a more durable asphalt. On this basis, sections 9 and 10 were determined to be the most durable and section 3 the least durable. Sections 9 and 10 contained asphalt that was one grade softer than any other asphalts and was ranked best in field performance. Otherwise, the 60-month data do not confirm or refute the better performance of viscosity-graded or penetration-graded asphalt cements.

No correlation was found between the air-void content and hardening of the asphalt in service. The lack of correlation can be explained partially by the relatively narrow range in voids after 5 years—approximately 3 to 5 percent.

No analysis was made of the effect of asphalt viscosity at 60 C (140 F) on rutting. However, a plot of rutting versus log of viscosity shows a fair correlation for 5 of the 6 viscosity-graded asphalts (Fig. 8).

Ohio

Experimental test sections were constructed in 4 areas of Ohio in 1968 (*65*). Altogether, 15 asphalts of varying properties were used. All asphaltic concrete mixtures were placed on existing portland cement concrete in two 1-in. (25-mm) overlays. All phases of construction were well controlled.

The purpose of the study was to evaluate asphalt paving mixtures containing asphalt cement graded by viscosity at 140 F (60 C) but having different penetrations, along with asphalts graded by penetration at 77 F (25 C) but having different viscosities.

Except for reflection cracks from the joints and cracks in the concrete, all of the test sections were rated good after three years service. The initial construction data showed that the void contents ranged from 9.3 to 14.0. The properties of the original asphalts, thin-film residues, and asphalt recovered from the pavement samples after three years of service were within the ranges given in Table 9. The void content of the mixtures were all high and probably would have some effect on the rate of hardening of the asphalt.

A final report covering 5 years of service was published in 1975 (*66*). All of the 19 test sections were found to be in good condition with the exception of reflection cracks. The study concluded:

- Viscosity grading resulted in uniform consistency from each producer.
- The findings of the study resulted in the adoption of a single grade AC20 specification by the Ohio DOT, Division of Highways.
- The adoption of one grade of asphalt resulted further in reduced need for asphalt storage tanks, reduced testing, and improved acceptance.

TRANSVERSE THERMAL CRACKING PROBLEMS

The problem of transverse thermal cracking of asphalt pavements is not new. Baskin and Le Bel reported in 1937 that the incidence of transverse cracking was common in many Canadian cities that were subjected to very low temperatures. Softer asphalt cements were often used in an attempt to solve the problem.

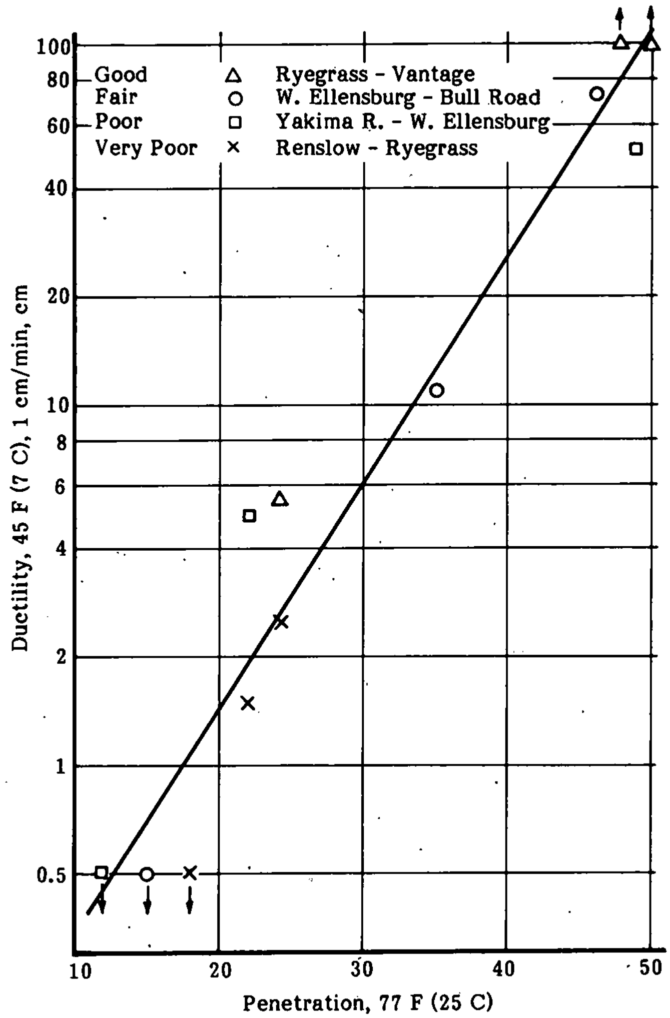

Figure 7. Relationship between penetration and ductility of recovered asphalts and pavement performance (from 62).

Several Canadian provinces constructed field and laboratory tests to determine the cause of transverse cracking and practical solutions to the problem. In 1960, an experimental road was constructed in Arkona, Ontario, using three different asphalts. The findings indicated that transverse cracking was related to the asphalt characteristics. In 1963, Saskatchewan initiated a research project to gather information on thermal transverse cracking. Since then, an extensive research effort has been under way to develop further information on the cause of and solution to the problem. There is little information in the early literature to indicate that transverse thermal cracking was considered a major problem in the United States. However, during the past 10 years, several studies have been reported. In some states, transverse thermal cracking is regarded as serious even though the freezing indices are generally low. The number of freeze-thaw repetitions may contribute to thermal transverse cracking.

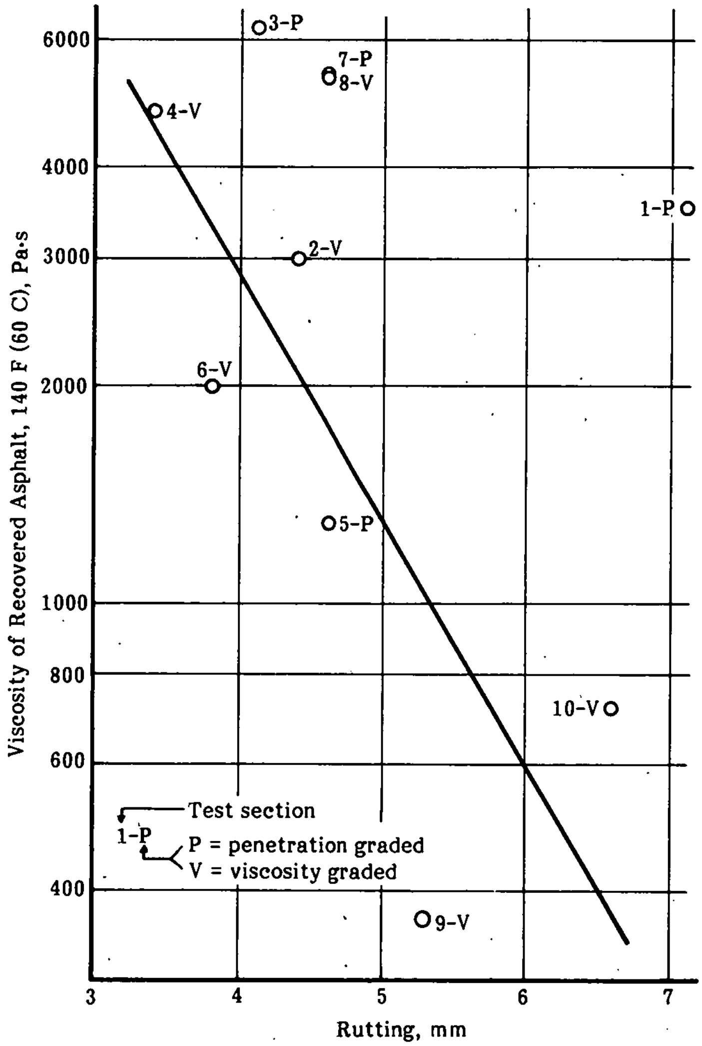

Figure 8: Relationship between rutting and viscosity of recovered asphalt after five years service (from 63).

The following discusses transverse cracking studies in the U.S. and Canada that show some relation between asphalt properties and the incidence of cracking.

Asphalt Institute Report

In 1973, at the request of the Asphalt Institute, Haas comprehensively documented methods for designing asphalt pavements to minimize low-temperature shrinkage cracking (*67*). Through extensive field studies of existing pavements, experimental test sections, observations, and laboratory evaluations, the importance of asphalt properties began to emerge. A number of agencies implemented the findings by revising their specifications or by using only softer grades of asphalt in cold areas; Haas considered this approach an indirect method of resolving the low-temperature cracking problem.

There is fairly widespread use of limiting stiffness in design methods. Stiffness is defined by van der Poel as the ratio of stress to strain for the loading method used and for the particular time and temperature of loading.

Haas pointed out that there are two general methods of determining stiffness of the bituminous material and mixtures. The first method is direct testing of mixtures. This consists of creep, relaxation, or constant rate-of-strain testing using tension, compression, dynamic, or flexural testing methods. The second method is indirect estimation of the stiffness of the bituminous material. The original van der Poel method (I); Heukelom's method (II); and McLeod's method (III), the pen-vis number (PVN), have been used. Brief descriptions and figures illustrating the three methods are given in Appendix A.

Haas noted the following limitations of the indirect methods for estimating the stiffness modulus of bituminous materials:

- It is not apparent which of the methods is most applicable to use in any particular case.
- In using van der Poel's and Heukelom's modified nomograph, extreme care must be exercised to obtain the required precision, due to the scale involved.
- No estimate of error is possible in determining stiffness by indirect methods, as compared with direct methods.
- Determining stiffness of a bituminous mixture by a series of transformations, starting from routine test data on the asphalt, appears unscientific to a number of engineers.

Haas concluded that, despite these limitations, the indirect methods are a valuable part of asphalt technology and that, if employed properly, they can be used to obtain initial estimates of stiffness modulus.

Studies of Transverse Cracking in the United States

South Dakota

In 1968, South Dakota made a survey of 189 asphalt pavements constructed throughout the state (*68*). The purpose was to determine the extent of transverse cracking and the relation of the cracking to the hardness or grade of asphalt used. Four grades of asphalt cement (85-100, 100-120, 120-150, and 200-300 penetration) and SC-6 road oil were used.

The primary conclusion of the study was that a definite relationship existed between asphalt hardness and pavement cracking. Pavements constructed with 85-100 penetration asphalt can be expected to develop transverse cracks at intervals of 50 ft (16 m) or less within 3 years. Pavements constructed with SC-6, the softest asphalt, showed little or no cracking after 10 years of service.

No attempt was made to determine the actual hardness of the asphalt in place or to relate cracking to the source of the asphalt. Figure 9 shows the amount of cracking in 172 of 189 pavements compared with the grade of asphalt used.

South Dakota reported a more detailed study of thermal cracking in 1976 (*69*). The conclusions were essentially the same as those reported earlier. A strong correlation was found between initial asphalt consistency and the frequency of cracking. The 1976 study revealed a greater resistance to crack development in the Black Hills area, where quarried limestone aggregates were used with all asphalt types, than throughout the rest of the state, where crushed gravel was used.

To verify the findings of the statewide survey, test sections were constructed side by side to compare both different grades of asphalt and limestone aggregate with crushed gravel. The comparisons included (a) crushed gravel with 85-100 penetration asphalt, (b) limestone with 85-100 penetration asphalt, (c) crushed gravel with 200-300 penetration asphalt, and (d) limestone with 200-300 penetration asphalt.

The conclusions were:

- Crushed gravel with 200-300 penetration asphalt significantly retarded transverse cracking, compared to gravel and 85-100 penetration asphalt.
- The use of limestone aggregate with 85-100 penetration asphalt produced about the same results as 200-300 penetration asphalts with gravel.
- A combination of 200-300 penetration asphalt and 100 percent crushed limestone produced a pavement with outstanding ability to resist crack formation.

Texas

In 1976, Benson reported a study of the properties of mixtures and asphalts that were associated with transverse cracking of asphaltic concrete pavements in central and west Texas (*70*). Some of the findings and conclusions of this study are:

- Thermally induced stresses are responsible for transverse cracking failures of some pavements in west and central Texas.
- Longitudinal cracks often accompany transverse cracking. There is some evidence that transverse cracks may cause longitudinal cracks.
- The amount of thermally induced cracking is related directly to the hardness of the asphalt binder.
- Control of asphalt hardening should be focused on the asphalt itself.
- Asphalt hardening rates follow a generalized pattern:

For penetration measurement, the form is

$$P = a + b \cdot \ln(t)$$

For viscosity measurement, the form is

$$V = at^b$$

P = penetration at 77 F (25 C)
V = viscosity at 77 F (25 C)
t = time from laydown in months
a and b = nondimensional coefficients derived from least squares regression analysis for short- and long-term hardening

Using Spearman's rank correlation coefficients on data from nine projects, the following correlations were obtained between transverse crack frequency and:

Viscosity at 77 F (25 C)	0.91
Hardening index, $\frac{\text{viscosity of aged asphalt}}{\text{viscosity of original asphalt}}$	0.85
Viscosity at 275 F (135 C)	0.58
Penetration, 32 F (0 C)	0.75
Penetration, 77 F (25 C)	0.68
Asphalt stiffness kg/cm²	0.74
Schmidt's M_R	0.12
Indirect tension	0.10
Voids, final, percent	0.89

Of primary interest is the fact that the highest correlation coefficients are viscosity at 77 F (25 C), hardening index, and voids.

Oklahoma

Noureldin and Manke reported on pavements at 9 test sites in Oklahoma that had various degrees of transverse cracking (*71*). Random core samples of 150 mm (6.0 in.) and 100 mm (4.0 in.) were obtained from each test site. The larger cores were used to study crack formation, and the smaller cores were used to determine low-temperature tensile properties. The asphalt was recovered from the core specimens, and stiffness modulus was determined at low temperatures. Test results on cores and recovered asphalt were analyzed, and correlations with the observed degree of pavement cracking were made using the Statistical Analysis System computer program.

Two conclusions of the study are important in relating asphalt properties to transverse cracking (durability). First, cracks originated in the surface and appear to have been caused by cold-temperature contraction of the asphaltic concrete surface layer. Second, stiffness moduli of recovered asphalts, determined at the lowest minimum temperature in central Oklahoma, were correlated with the cracking indexes of the pavement test sites. The stiffer or harder the asphalt cement in a pavement, the greater was the degree of transverse cracking. The lowest temperature in the test site area was estimated to be —10 F (—23 C). McLeod's pen-vis number was used to calculate stiffness moduli.

Pennsylvania

Pennsylvania constructed 6 test pavements in 1976 using AC-20 asphalts from different sources (*72*). The objectives were to (a) study the changing asphalt properties in the aging pavements in service, (b) determine the effect of

TABLE 9

PROPERTIES OF ORIGINAL ASPHALTS AND ASPHALTS RECOVERED FROM PAVEMENTS IN OHIO (*65*)

Viscosity, original, 140 F (60 C) poises	1207 - 2557
Viscosity, thin-film residue, poises	1450 - 9016
Viscosity, recovered asphalt, poises	1849 - 44070
Penetration, original, 77 F (25 C)	60 - 100
Penetration, thin-film residue, 77 F (25 C)	37 - 68
Penetration, recovered asphalt, 77 F (25 C)	23 - 56
Ductility, original, 77 F (25 C) cm	150+
Ductility, original, 45 F (7 C) 1 cm/min, cm	7 - 53
Ductility, thin-film residue, 77 F (25 C) cm	100+
Ductility, recovered asphalt, 77 F (25 C) cm	13 - 100+

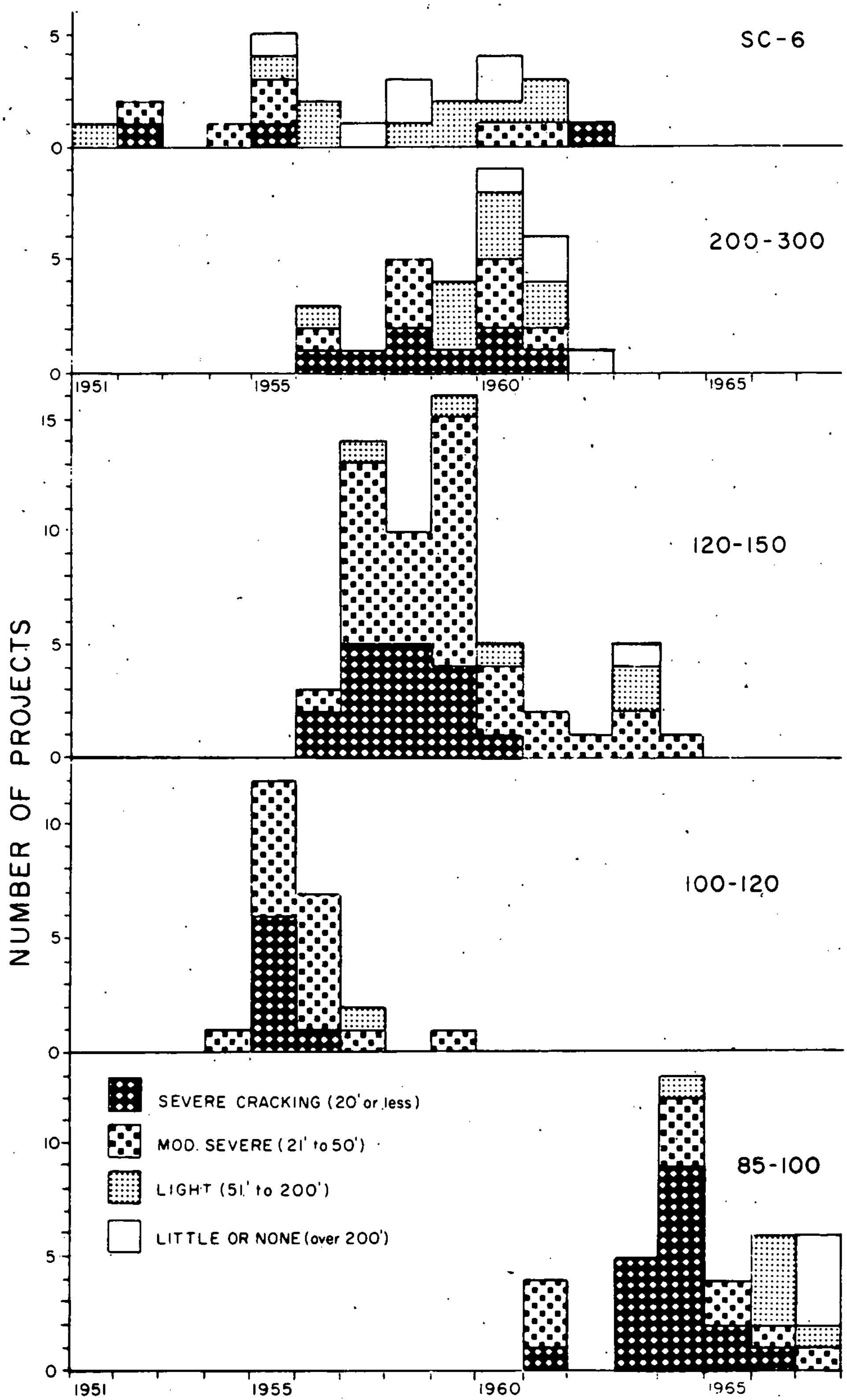

Figure 9. Pavement cracking as related to asphalt hardness (South Dakota) (67).

rheological properties at 77 F (25 C) or lower on the pavement performance and durability, and (c) develop suitable specifications for AC-20 asphalt cement to ensure durable pavements.

The test pavements were located in an area of Pennsylvania that is relatively cold, and thus the pavements would be expected to develop transverse thermal cracking. The temperature at the nearest weather station was recorded at −20 F (−29 C) during the winter of 1976-1977. Visual observations revealed that two of the six pavements did develop low-temperature cracking. The two test pavements were constructed with asphalt from the same source, but the rheological properties varied to some degree.

The temperature susceptibility of the asphalts was determined by three methods: (a) the van der Poel nomograph method (*73*), (b) the Heukelom modification of the nomograph (*74*), and (c) the McLeod method (PVN) (*75*). These methods are described in Appendix A.

A comparison of values for stiffness moduli of the original asphalt obtained by the three methods shows that the magnitude of the differences between the van der Poel method and the McLeod method is smaller than that obtained by the Heukelom method. All three methods show that the two asphalts that developed excessive low-temperature cracking had the highest stiffness moduli.

The stiffness moduli of the recovered asphalts also were determined by the three methods at −10 F (−23 C) and −20 F (−29 C) for 20,000 sec loading time. Fromm and Phang have used a limiting stiffness modulus of 20,000 psi (138 MPa) for 10,000 sec loading time to reduce cracking (*76*). Two asphalts that showed early cracking had stiffness moduli over that limit. McLeod has used a stiffness modulus of 1×10^6 psi (6900 MPa) at the lowest pavement temperature to indicate low-temperature cracking. The two Pennsylvania pavements that showed low-temperature cracking developed stiffness at McLeod's limit or more at −10 F (−23 C).

The stiffness moduli of the paving mixtures (derived from the stiffness moduli of the recovered asphalts) were determined by the three methods at −10 F (−23 C) and 20,000 sec loading time (Table 10). An interesting note is the fact that the results by the three methods agree in decreasing order of aged mix stiffness. Pavements T-1 and T-5 contain the most temperature-susceptible asphalts and developed excessive low-temperature cracking.

Kandhal proposed a specification requirement for cold regions in Pennsylvania for AC-20 asphalt cement using a maximum permissible stiffness modulus of 275 kg/cm² (27 MPa; 3900 psi) at the minimum pavement temperature and 20,000 sec loading time (*72*).

TABLE 10

STIFFNESS MODULI OF AGED ASPHALT MIXTURES USED IN PENN. STUDY (10^5 psi) (*72*)

Pavement	van der Poel	Heukelom	McLeod
T-1	10	17	11.5
T-5	8.5	14	10
T-4	6.8	4.6	8
T-2	4.6	4.4	4.8
T-3	4.1	4.1	4.4
T-6	3.15	3.15	3.4

Note: Moduli determined at -10 F (-23 C) with loading time of 20,000 sec.

Studies of Low-Temperature Cracking in Canada

Perhaps the greatest incidence of low-temperature thermal cracking has been experienced in the Canadian provinces. The following is some of the documented research on the subject.

Saskatchewan

In 1963, Saskatchewan initiated a research project to gather information on transverse cracking (*77*). Full-scale in-service test sections were constructed so that the effect of the asphalt source, the penetration grade of the asphalt cement, and the thickness of the base course on the frequency of transverse cracking could be studied. The asphalts were used on separate construction projects. The performance of the test sections showed that a significant relationship existed between the frequency of cracks and the asphalt supplier.

Based on the performance of the test sections, specifications for asphalt cement were changed to lower the allowable variation of penetration and viscosity requirements for asphalts from different sourecs. Four grades (AC-1.5, AC-4, AC-5, and AC-6) were adopted. AC-1.5 [120-180 Pa·s at 140 F (60 C)] is used on low-traffic roads. AC-5 and AC-6 are used on primary, higher-traffic roads.

A second series of tests was constructed in 1966. Asphalts from four refineries, conforming to the new specifications, were used on separate projects. Hardening of the asphalts during construction and after 12 months of service was determined. The various test sections using different asphalts showed different amounts of cracking, but the difference could not be associated with the asphalt source. However, it should be noted that the ranges in penetration at 77 F (25 C) and viscosity at 140 F (60 C) were relatively narrow and all of the asphalts could be considered low-temperature susceptible.

Alberta

The high occurrence of transverse cracking in Alberta prompted studies to determine the contribution of environment, materials, and construction practices to the problem (*78*). Observations were made on 20 pavements, and laboratory tests were made on representative samples from each of the projects. Asphalt for these pavements was obtained from 10 suppliers. With some exceptions, the higher frequency of cracking appeared to be associated with certain asphalt sources. Examination of the mixtures failed to reveal any particular design or field properties that were clearly associated with the observed cracking frequency. Also, the temperature-viscosity relationships at various shear rates failed to provide a satisfactory means of predicting low-temperature cracking. Ductility testing proved inconclusive and was abandoned early in the program.

In 1966, the Alberta Department of Highways constructed experimental test sections using three 200-300 penetration asphalt cements of low, medium, and high viscosities at 140 F (60 C) (*79*). The study showed that the pavement section containing the lowest-viscosity asphalt developed transverse cracks earliest, and the density of that mixture increased the most under traffic. The authors also studied the tensile splitting test on mixes with the three asphalts. Comparisons showed that the pavement with the highest crack frequency had the lowest failure strain and the highest failure stress and failure stiffness. The authors concluded that the tensile splitting test can be used to measure low-temperature stiffness.

In 1967, Alberta adopted a specification requiring a minimum penetration of 250 at 77 F (25 C) and a minimum viscosity of 275 poises (28 Pa·s) at 140 F (60 C). Under normal conditions this has resulted in a more uniform product, a reduction of early low-temperature transverse cracking, and the elimination of tender mixes.

Ontario

In 1972, McLeod reported on the performance of three test roads constructed in Ontario after 8, 9, 10, and 11 years of service (*80*). Three 85-100 penetration asphalts from three different suppliers and having different temperature susceptibilities were used on each test road. Within a test road, the aggregates, mixture design, mixing plant, and construction crew were the same for each asphalt source. However, different aggregates and different contractors were used on each 6-mile test road.

The rate of transverse crack development differed for each asphalt supplier and each test road. The susceptibility of the three asphalts to temperature was determined by the penetration index (PI) developed by Pfeiffer and Van Doormaal (*81*) and by the pen-vis number developed by McLeod. A summary of the incidence of transverse cracking and temperature susceptibility is given in Table 11.

McLeod recognized that the order of increasing or decreasing in pen-vis numbers is completely opposite from the ranking of PI numbers for the asphalts included in his report.

The pen-vis numbers for the asphalts used in the three road trials were calculated from penetration at 77 F (25 C) and kinematic viscosity at 275 F (135 C). The procedure for determining the values is included in Appendix A. A method for determining the pen-vis number by use of penetration at 77 F (25 C) and viscosity in poises at 140 F (60 C) also can be used. Unfortunately, the 140 F (60 C) viscosities are not reported for the asphalts used in the three roads; thus the pen-vis numbers on this basis are not given. Table 12 gives more detailed results of cracking and properties of the original and recovered asphalts.

A summary of the report includes these important facts:

- The relationship between transverse cracking and the Pfeiffer and Van Doormaal penetration index is the opposite of general findings by other investigators.
- The pen-vis number was devised using penetration at 77 F (25 C) and kinematic viscosity at 275 F (135 C) or 140 F (60 C).
- In all test roads, the number of transverse cracks increased markedly with a decrease in the pen-vis number of the asphalt cement.
- A chart was developed to assist in the selection of a grade of asphalt cement that would eliminate transverse cracking.

The Ontario Department of Highways had experienced considerable difficulty with some asphalt cements supplied for hot plant-mix construction (*76*). The source of the trouble finally was recognized as high temperature sensitivity (high temperature susceptibility).

1. These asphalts produced fluid mixtures that were hard to lay and compact. In some cases they set slowly.
2. Reduction in mixing temperature sometimes caused moisture-drying problems.
3. Pavements constructed with high temperature-susceptible asphalt cements had a greater tendency to flush than those constructed with asphalts that were less temperature susceptible. Two different test pavements using the two types of asphalt cement confirmed this flushing problem.
4. Some pavements constructed with the high temperature-susceptible asphalt cements exhibited severe transverse cracking after only a few winters of use.

A study of the asphalts supplied to Ontario revealed that the 85-100 penetration asphalts having low temperature susceptibility had viscosities in the range of 360 to 460 centistokes (360 to 460 mm²/s) at 275 F (135 C) and that those causing tender and slow-setting mixtures, flushing, and more transverse cracking had viscosities in the range of 160 to 220 centistokes (160 to 220 mm²/s). For 150-200 penetration asphalts, the viscosity of the problem group was in the range of 120 to 160 centistokes (120 to 160 mm²/s) and the good performing group was around 240 to 300 centistokes (240 to 300 mm²/s).

In the case of the 85-100 penetration asphalts, the ductility at 39.2 F (4 C), 1 cm per sec, was low (6 to 12 cm) for the high temperature-susceptible asphalts and 15 cm or more for the less temperature-susceptible materials.

As a result of this study, the Ontario Department of Highways adopted specifications incorporating minimum requirements for viscosity at 275 F (135 C) and ductility at 39.2 F (4 C), 1 cm per sec.

In 1972, Fromm and Phang reported the findings of a field survey of asphalt pavements started in 1966 in Ontario (*82*). Thirty-three pavements constructed under normal contracts were investigated. Cracks were counted, and

TABLE 11

INCIDENCE OF TRANSVERSE CRACKING ON TEST ROADS IN ONTARIO (*80*)

	Transverse Cracks per Lane Mile (Type 1)*		
Asphalt Supplier —	1	2	3
Test road No. 1	46	176	294
Test road No. 2	14	37	158
Test road No. 3	9	21	152
Penetration index	-1.00	-0.57	-0.21
Pen-vis No.	-0.19	-0.36	-1.34

*Type 1 cracks extend full width of pavement

TABLE 12

PERFORMANCE OF ONTARIO TEST ROADS AND PROPERTIES OF THE ORIGINAL AND RECOVERED ASPHALTS (*80*)

Test Road	Asphalt Supplier	Transverse Cracks per Mile (a) Type 1	Transverse Cracks per Mile (b) Type 2	Properties of Recovered Asphalt: Penetration at 77 F (25 C)	Pen-Vis Number Orig.	Pen-Vis Number Rec.	Viscosity 275 F (135 C) Orig. (centistokes)	Viscosity 275 F (135 C) Rec. (centistokes)	Ductility Recovered AC 77 F (25 C) 5 cm/min (cm)	Ductility Recovered AC 39.2 F (4 C) 1 cm/min (cm)
1	1	46	40	30	-.19	-.59	460	770	150	3.3
	2	176	61	34	-.36	-.62	365	654	71	4.9
	3	294	22	31	-1.34	-1.36	210	409	20	.0
2	1	14	53	51	-.19	-.46	460	589	150	4.3
	2	37	16	37	-.36	-.58	365	659	99	5.6
	3	158	30	41	-1.34	-1.34	210	334	69	.0
3	1	9	34	43	-.19	-.52	460	597	150+	2.6
	2	21	26	52	-.36	-.61	365	481	150+	.0
	3	152	44	37	-1.34	-1.41	210	339	46	.0

(a) Type 1 cracks extend full width of pavement
(b) Type 2 cracks extend from outside edge toward centerline of pavement

the materials in all layers of the pavement, including the subgrade, were analyzed in the laboratory.

Several methods of analyzing the large amount of data were considered, and a stepwise regression analysis was chosen. The authors described the method used to reduce the variables and to develop mathematical models of transverse cracking. Penetration at 77 F (25 C) and the ratio of viscosity in megapoises at 60 F (16 C) to the viscosity in centistokes at 275 F (135 C) were used to show the temperature susceptibility of the asphalts.

The authors concluded that:

- Transverse cracking is largely a temperature phenomenon. The cracking is more severe in an area having a high freezing index.
- Asphalts having good flow properties at low temperatures lead to lower frequency of transverse cracks.
- Transverse cracking of bituminous pavements can be reduced or retarded by the use of softer asphalts or asphalts that are less temperature susceptible.
- The stiffness modulus is a major factor governing transverse cracking.

Ste. Anne Test Road

The performance of the Ste. Anne test road and the relationship between laboratory and road observations were discussed in two reports (*83, 84*). The reports contained the following conclusions:

- Cracking started at the surface when the thermal stresses exceeded the breaking strength at low temperatures.
- The most critical influence on pavement cracking severity was the asphalt binder, and increased cracking tendency was noted in the following order:

SC-5		No cracking
HV 150/200	PI-1.0	Light cracking
LV 300/400	PI-2.9	Severe cracking
LV 150/200	PI-2.7	Most severe cracking

- Observed road cracking correlated with asphalt stiffness at low temperatures. Both increasing temperature susceptibility (decreasing PI) and decreasing penetration resulted in higher cracking.
- Cracking temperatures predicted from a nomograph, based on asphalt penetrations at 5 and 25 C (41 and 77 F), show good agreement with initial transverse cracking observations and confirm that the nomograph can be used to compare the initial relative cracking tendencies of different asphalts and road mixtures.
- Asphalt stiffness predictions from van der Poel's nomograph, based on penetration and softening-point data or penetration-viscosity data (i.e., pen-vis number and base temperature), are inadequate for waxy asphalts at moderate temperatuers (around 25 C—77 F) and long loading times. Precooled penetration data show the best agreement between predicted and experimental values.

Air-Blown Asphalts and Thermal Cracking

Recently studies have been initiated in Canada to determine whether mild air-blowing of some of the asphalt cements would improve the temperature susceptibility and result in less thermal cracking. If air blowing will reduce the frequency of cracking, harder asphalts could be used to reduce rutting that may occur with softer asphalts.

Saskatchewan

Clark and Culley described a full-scale test section that was constructed in central Saskatchewan in 1973 to evaluate the performance of air-blown asphalts used to reduce thermal cracking (*85*). The penetration and viscosity characteristics of the asphalt cements are given in Table 13.

The pavement sections were 7.5 in. (190 mm) of full-depth asphalt concrete with Saskatchewan-type crushed ag-

TABLE 13

AIR-BLOWN AND STANDARD ASPHALT CEMENTS USED IN SASKATCHEWAN (*85*)

Asphalt Cement	Penetration 77 F (25 C)	Viscosity 140 F (60 C), Pa·S
Standard AC-5	207	47
Air-blown 100 AB	88	338
Air-blown 150 AB	139	136

gregate having a maximum size of ⅝ in. (16 mm). The properties of the mixtures and asphalts before and after 6, 12, and 24 months were determined. Stiffness values also were determined by van der Poel's nomograph at —40 C (—40 F) and by the sliding plate rheometer developed by Fenijn and Krooshof (*86*). The latter method permits direct measurement of asphalt stiffness at 0 C (32 F) through the range of 10^3 to 10^9 Pa (1.45×10^{-1} to 1.45×10^5 psi). Studies with the rheometer will continue at lower temperatures.

After 24 months, the stiffness had not reached critical values and cracking was minimal. A summary of the performance of the test sections and stiffness relationships of the original asphalt and the asphalt after 24 months service is shown in Figure 10.

Manitoba and Ontario

Gaw and Burgess of Shell Oil Co. and Young and Fromm from Manitoba and Ontario, respectively, described laboratory and field studies on the use and performance of air-blown asphalt cements produced from waxy crudes (*87*). The waxy crudes normally produce low-viscosity asphalts that have been associated with low-temperature (thermal) cracking. Pavement test sections were constructed on the Trans-Canada Highway in Manitoba in 1971 and in northern Ontario in 1973.

Manitoba Test Road. Blown, low-viscosity asphalts of 150-200 penetration (BLV 150-200) and 100-150 penetration (BLV 100-150) were compared with high-viscosity 300-400 penetration (HV 300-400), 200-300 penetration (HV 200-300), and SC-5 surfacing mixtures (*87*). No cracking was observed in any of the test sections after the first two years of service. Minimum air temperature was —41 C (—42 F). During the third year, temperatures dropped to —44 C (—47 F). Extensive hairline cracking was observed in the BLV 100-150 section, and a few less-obvious cracks developed in the BLV 150-200 section. During the fourth winter, the minimum temperature was —36 C (—33 F), and cracking in both the BLV sections became more distinct. No cracking was found in the HV 200-300, the HV 300-400, and the SC-5 sections.

The cracking in the BLV 100-150 and BLV 150-200 test sections was predominantly transverse, but longitudinal wheel path cracking was also significant. The performance of the blown and conventional asphalts is given in Table 14. No cracking was observed in the HV 200-300, HV 300-400, and SC-5 sections after 4 years. The cracking in the BLV test sections was not typical of the transverse thermal cracking usually observed. However, the authors indicate that the cracking in the BLV was a substantial improvement over the cracking in pavements constructed with low viscosity (LV) asphalts.

Northern Ontario Test Road. The test road in northern Ontario was constructed in 1973 on Highway No. 11 with the following types and grades of asphalt (*87*).

- Blown low-viscosity asphalt, 150-200 penetration (BLV 150-200).

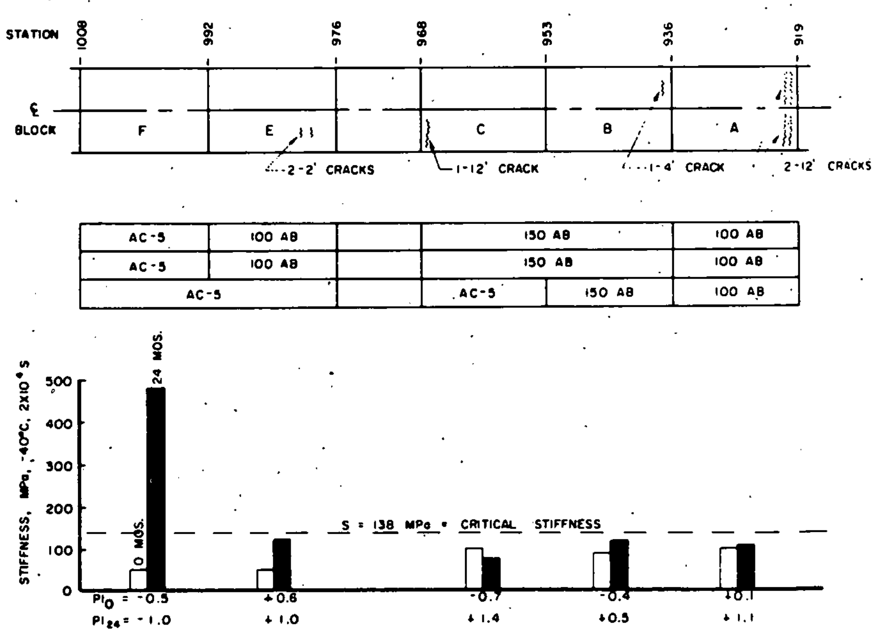

Figure 10. Transverse cracking-stiffness relationships at 24 months (85).

• Blown low-viscosity asphalt, 85-100 penetration (BLV 85-100).
• High-viscosity asphalt, 150-200 penetration (HV 150-200).

The low-viscosity asphalts were blown to meet low-temperature cracking properties.

For the Ontario test, minimum air temperatures reached −39 C (−38 F) during the first two years, with no cracking in either the blown asphalt sections or the control sections. During the third winter, with minimum temperatures of −38 C (−36 F), moderate transverse cracking occurred in the HV 150-200 (control) section. No significant cracking developed in the low-viscosity 150-200 and the 85-100 test sections. This confirmed that the air-blown, low-viscosity asphalts have crack resistance that is superior to that of the HV 150-200 asphalt.

• The laboratory and field study confirmed that good low-temperature performance of blown, low-viscosity asphalts can be expected.
• Air blowing of low-viscosity, waxy asphalts improves temperature susceptibility and results in better resistance to low-temperature cracking. Performance of the Manitoba and Ontario roads after 3 or 4 years service is shown in Table 14.
• The changes in the asphalts in service are primarily in the form of improvements in the low temperature-susceptibility characteristics of the low-viscosity waxy asphalts.
• No detrimental road performance was found. No evidence was found that the high wax content of the blown, low-viscosity asphalts caused abnormal raveling or stripping.

New Test Methods

Researchers have noted that the stiffness modulus of the asphalt is a primary factor in the transverse cracking problem. At present, the stiffness can be measured directly or can be predicted indirectly from van der Poel's or Heukelom's nomograph or by McLeod's PVN. Several researchers have pointed out that such predictions can be significantly in error if incorrect entrance parameters are used. For a waxy asphalt, for example, direct measurements would be preferred for maximum reliability.

In 1970, Fenijn and Krooshof reported the development of a sliding-plate rheometer by Koninklijke/Shell-Laboratorium in Amsterdam (*86*). They believed that the instrument provided a simple, reliable, and inexpensive means of measuring the viscoelastic behavior of bitumens. Creep tests can be carried out under shear conditions, enabling the determination of stiffness in the range of 10^3 to 10^9 Pa. The instrument is available commercially from Enraf-Nonius, Delph.

TABLE 14

PERFORMANCE OF AIR-BLOWN ASPHALT TEST SECTIONS AFTER 3 AND 4 YEARS (*87*)

Type of Binder	Amount of Cracking After: 3 years	4 years
Manitoba		
BLV 150-200	Few cracks	Some transverse and longitudinal cracking
BLV 100-150	Extensive* hairline cracking	Extensive transverse and longitudinal cracking
HV 200-300	No cracking	No cracking
HV 300-400	No cracking	No cracking
SC-5	No cracking	No cracking

*Cracking was not the typical transverse thermal cracking that generally had been observed in other test roads

Type of Binder	Amount of Cracking After: 3 years	4 years
Ontario		
BLV 150-200	Not significant	
BLV 85-100	Not significant	
HV 150-200	Moderate	

In 1978, Gaw reported that the sliding-plate rheometer had been modified to permit measurements of stiffness up to 1.5×10^9 Pa at temperatures in the range where pavements crack (*88*). His report showed that air-blowing significantly influences the low-temperature asphalt stiffness. An air-blown, 85-100 penetration asphalt was shown to have a lower low-temperature stiffness than a flashed, 150-200 penetration asphalt from the same crude source.

Schweyer, Smith, and Fish reported on further development of a rheometer that would provide a simple, rapid procedure for routine measurement of the viscosity of asphalt cements approaching and perhaps exceeding 10^9 poises (10^8 Pa·s) in the low-temperature range (*89*). Schweyer's rheometer also is capable of evaluating the shear rate under a constant stress. The method may provide a means of directly evaluating the low-temperature properties of asphalt cements that are of concern in areas where there are thermal cracking problems. In general, results at 5 C (41 F) provide information on the rheological behavior of the asphalts at this low temperature.

In 1978, Schweyer and Burns reported on further study of the rheometer. They used a variety of asphalts to demonstrate differences that can be found in test data using empirical methods and direct measurements (*90*). The Schweyer rheometer provides a means of measuring rheological properties in fundamental units at low temperatures. It should be useful in evaluating the stiffness of asphalts and the relation to thermal cracking.

CHAPTER THREE

CONCLUSIONS AND RECOMMENDATIONS

For more than 80 years, engineers, researchers, and asphalt technologists have been concerned with the properties of asphalt cements that could be used to predict and control the durability of pavements. Prior to 1890, few factual data were published showing the relation of the properties of the asphalt cements to pavement durability. Those directly involved with the construction of asphalt pavements relied primarily on experience and subjective observations.

Most of the asphalt cements used in the 1890s and early 1900s were imported from Trinidad and Bermudez; these were solid bitumen materials that were blended with fluxes to reduce their consistency. The fluxes contained variable amounts of volatile material that evaporated during blending, hot-plant mixing, and aging in the pavements. The first attempts to control hardening of asphalt were directed to controlling the volatility of the fluxes. Thus, oven heat tests were developed and standardized. At about the same time, the penetration test was developed and standardized. It provided a means to measure the consistency of the asphalt before and after subjection to oven heat tests.

The development of the recovery test by Abson in 1933 provided a means of recovering the asphalt from hot-plant mixtures immediately and after periods of aging in the pavement. Through the past 45 years, much progress has been made, and an appreciable amount of information on the changes in asphalt properties and the relation of the properties to pavement performance has been published. However, users are still concerned that asphalt produced from other sources and refining methods will differ from the asphalt they are familiar with and new problems will develop.

The intent of this synthesis was to review the literature and bring together the existing information on the relationship of asphalt cement properties to pavement durability. Anyone familiar with asphalt pavements is aware that many factors influence the performance or durability of both the asphalt cement and the pavement. The reader should recognize that the information presented here does not analyze the effect of outside variables on the performance of asphalt and its relation to pavement durability. A very extensive study would be required to review and make a complete analysis of all the variables involved.

Substantial information and data have been developed showing that void content of mixes is of major importance when considering the durability of asphalt cements and pavements. In some of the studies reported here, void content data were not given. In other studies, the void contents were included and have been recognized in this synthesis.

In reviewing the literature, a number of reports were not included because they lacked direct information on either field performance or asphalt properties. With few exceptions, laboratory studies of asphalt cements and mixtures were not reported. The information in this report relating asphalt properties to pavement durability was obtained from four sources that can be summarized as follows:

- Uncontrolled test sections—pavements constructed under normal contract procedures. Asphalt cements, aggregates, mixture design, mixing and laying temperatures, compaction, and selection of sample locations may differ.
- Semi-controlled test sections—sections of pavements constructed with different asphalts in place of the job asphalt. Properties of the asphalt before paving and in the pavement were known.
- Controlled test sections—pavements constructed as experimental projects using different asphalts. All other variables were controlled to the best degree possible.
- Transverse cracking test sections—pavements constructed under semi-controlled or controlled conditions in areas where transverse cracking is a recognized problem.

The approximate numbers of test areas of the above types were:

Uncontrolled test sections	388
Semi-controlled test sections	86
Controlled test sections	143
Transverse cracking test sections	163 (Canadian)

The point should be emphasized that the number of test sections showing distress was not necessarily due to lower quality asphalts. The scope of the synthesis excluded the effect of external factors on the behavior of the asphalts that could be associated with pavement distress or durability.

Of the total test areas, distress in the form of cracking or shoving was found in 198 of the 388 uncontrolled test sections, 21 of 86 semi-controlled test sections, and 5 of 143 controlled test sections. Due to the variable extent of the transverse cracking within the test sections, the number of distressed sections was not determined.

The most significant information from the semi-controlled and fully controlled test sections is the relatively small amount of distress reported (26 of 229 test sections or about 11 percent). This compares to about 51 percent for the uncontrolled test sections. Perhaps the general upgrading of asphalt specifications by many agencies has resulted in the supply of higher quality and more uniform asphalts for those projects. Improved mixture design and construction control could be other significant factors reflecting in higher pavement durability.

The large amount of distress reported for the uncontrolled test sections was due primarily to the use of asphalts of too low penetration or too high viscosity as well as normal or excessive hardening of the asphalt during construction or in service.

Similarly, the large number of test sections that showed thermal transverse cracking was due primarily to the use of asphalts having excessively high stiffness in relatively cold regions. However, the South Dakota study shows less transverse cracking with crushed limestone aggregate. The effects of the original consistency, temperature susceptibility, and age hardening on the stiffness modulus have been well established.

Over-all, the performance data point out the importance of selecting the proper grade of asphalt to accommodate the environmental and traffic loading conditions. Some of the Canadian provinces have resorted to the use of softer asphalts such as 200-300 and 300-400 penetration in the colder regions to reduce the incidence of thermal cracking. South Dakota also found that the use of 200-300 penetration asphalts greatly reduced the amount of transverse cracking compared to pavements constructed with 85-100 penetration asphalts.

A number of concepts have been proposed and used to control or minimize the transverse cracking problem. Some of the concepts for which requirements are proposed include:

- Low-temperature penetration.
- Low-temperature ductility.
- Penetration-viscosity relationships.
- Methods to determine asphalt and mix stiffness by: (1) direct testing of mixtures using measurements of creep and relaxation under either tension or compression loading, or (2) indirect testing based on properties of the asphalt and transposed to mixture stiffness using empirical assumptions. Indirect methods include:

a. Penetration Index—by van der Poel
b. Penetration Index—modified by Heukelom
c. Penetration-Viscosity Number (PVN) by McLeod

There is some evidence that indirect methods rate the stiffness moduli of different asphalts in approximately the same order.

Finn et al. have used the Bayesian analysis method to predict pavement distress (*91*). Regression analysis, including four designer-controlled variables, is used to predict fatigue life. The results indicate that fatigue life increases as asphalt penetration, asphalt content, proportion of asphalt concrete (thickness), and base density increase. This synthesis provides information that should be useful in the Bayesian analysis.

CONCLUSIONS

The primary conclusion, based on the information presented in this synthesis, is that the hardness of the asphalt is the one property most closely associated with performance of pavements. The hardness of the asphalt in the pavement depends on:

- The initial selection of the proper penetration or viscosity grade of asphalt to accommodate pavement design life and environmental and traffic loading conditions.
- The temperature-susceptibility characteristics of the asphalt.
- The susceptibility of the asphalt to hardening during hot-plant mixing and construction of the pavement.
- The rate of hardening of the asphalt in the pavement in service.
- Asphalt-aggregate interactions such as adsorption or selective sorption of asphalt components.

The following test methods are adequate to measure and control hardening of asphalt cements during hot-plant mixing and in service:

- Thin-film or rolling thin-film tests for determining relative hardening in hot-plant mixing.
- Consistency tests at two or more temperatures to measure temperature susceptibility characteristics other than for very low temperatures.
- The Shell, California, or Chevron microfilm aging test to determine resistance of asphalts to hardening in service in the pavement.

RECOMMENDATIONS

- Develop criteria for selecting asphalt cements to accommodate pavement design and temperature and traffic loading conditions.
- Develop a standard method for sampling existing pavements to account for variability.
- Develop a standard method for determining stiffness modulus of asphalt using an indirect method.
- Develop a standard method for directly measuring low-temperature properties to determine asphalt stiffness.
- Tests based on inverse gas-liquid chromatography should be explored further as a means of studying asphalt-aggregate interactions that affect the performance of asphalts in relation to pavement durability.

REFERENCES

1. CRUM, R. W., "Research Attack on Bituminous Road Problems." *Proc., 2nd Ann. Montana Nat'l. Bituminous Conf.* (1938).
2. ABSON, G., "Apparatus for the Recovery of Asphalts." *Proc., ASTM,* Part II, Vol. 33 (1933).
3. BATEMAN, J. H., and DELP, C., "The Recovery and Examination of Asphalt in Paving Mixtures." *Proc., ASTM,* Part II, Vol. 27 (1927).
4. BUSSOW, C., "Notes on a Method of Recovering Bitumen from Paving Materials." *Proc., AAPT,* Vol. 7 (1936).
5. TRAXLER, R. N., and SCHWEYER, H. E., "Increase in Viscosity of Asphalt With Time." *Proc., ASTM,* Part II, Vol. 36 (1936).
6. HVEEM, F. N., "Quality Tests for Asphalts—a Progress Report." *Proc., AAPT,* Vol. 15 (1943) pp. 111-152.
7. FINN, F. N., "Factors Involved in the Design of Asphaltic Pavement Surfaces." *NCHRP Report 39* (1967) 112 pp.
8. RADER, L. F., "Correlation of Low Temperature Tests With Resistance to Cracking in Sheet Asphalt Pavements." *Proc., AAPT,* Vol. 7 (1936).
9. RADER, L. F., "Report on Further Research Work on Correlation of Low Temperature Tests With Resistance to Cracking of Sheet Asphalt Pavements." *Proc., AAPT,* Vol. 8 (1937).
10. HUBBARD, P., and GOLLOMB, H., "The Hardening of Asphalt with Relation to Development of Cracks in Asphalt Pavements." *Proc., AAPT,* Vol. 9 (1937) pp. 165-194.
11. BASKIN, C. W., and LEBEL, P., Discussion of paper by Hubbard and Gollomb. *Proc., AAPT,* Vol. 9 (1937).
12. POWERS, J. W., "Hardening of Asphaltic Cement in Asphalt Concrete Pavements." *Proc., Montana Nat'l. Bituminous Conf.* (1937).
13. RASCHIG, F. L., and DOYLE, P. E., "Some Recent Research on Asphalt Pavements." *Proc., AAPT,* Vol. 8 (1937).
14. MILLER, J. S., HAYDEN, H. P., and VOKAC, R., "Correlation of Physical Tests With Service Behavior of Asphaltic Mixtures—Final Report." *Proc., AAPT,* Vol. 10 (1939).
15. SHATTUCK, C. L., "Measurement of the Resistance of Oil Asphalts (50-60 Pen.) to Changes in Penetration and Ductility at Plant Mixing Temperatures." *Proc., AAPT,* Vol. 11 (1940) pp. 186-203.
16. LEWIS, R. H., and WELBORN, J. Y., "A Study of the Effect of Characteristics of Asphalt on the Physical Properties of Bituminous Mixtures." *Proc., AAPT,* Vol. 17 (1948) pp. 228-263. Also *Public Roads,* Vol. 25, No. 5 (Sept. 1948) pp. 85-94.
17. HALSTEAD, W. J., "Relation of Asphalt Ductility to Pavement Performance." *Public Roads,* Vol. 32, No. 10 (Oct. 1963) pp. 221-232.
18. PHELPS, H. E., "An Evaluation of Trends Toward the Use of Softer Asphalts." *Proc., Montana Nat'l. Bituminous Conf.* (1939).
19. BUCHANAN, J. E., "Obtaining Crack Free Performance in Asphalt Pavements." *Asphalt Forum,* Vol. 11, No. 5 (1938).
20. NICHOLSON, V., "A Laboratory Oxidation Test for Asphaltic Bitumens." *Proc., AAPT,* Vol. 9 (1937) pp. 208-214.
21. RASCHIG, F. L., and DOYLE, P. C., "A Laboratory Oxidation Test." *Proc., AAPT,* Vol. 9 (1937) pp. 215-217.
22. LEWIS, R. H., and WELBORN, J. Y., "The Physical and Chemical Properties of Petroleum Asphalts of the 50-60 and 85-100 Penetration Grades." *Public Roads,* Vol. 21, No. 1 (Mar. 1940) pp. 1-26. Also, *Proc., AAPT,* Vol. 11 (1940) pp. 86-157.
23. LEWIS, R. H., and WELBORN, J. Y., "The Properties of the Residues of 50-60 and 85-100 Penetration Asphalts From Oven Tests and Exposure." *Public Roads,* Vol. 22, No. 2 (Apr. 1941) pp. 27-48.
24. OLIENSIS, G. L., "A Quality Test for Determining the Degree of Heterogeneity of Asphalts." *Proc., ASTM,* Vol. 33, Part II (1933).
25. OLIENSIS, G. L., "A Further Study of the Heterogeneity of Asphalt—A Quantitative Method." *Proc., ASTM,* Vol. 36, Part II (1936).
26. BENSON, J., "Microscopic Reactions in Translucent Films." *Proc., AAPT,* Vol. 9 (1937) pp. 102-137.
27. PAULS, J. T., and WELBORN, J. Y., "Studies of the Hardening Properties of Asphaltic Materials." *Proc., AAPT,* Vol. 21 (1952).
28. GRIFFIN, R. J., MILES, T. K., and PENTHER, C. J., "Microfilm Durability Test for Asphalt." *Proc., AAPT,* Vol. 24 (1955) pp. 31-62.
29. HEITHAUS, J. J., and JOHNSON, R. W., "A Microviscometer Study of Road Asphalt Hardening in the Field and Laboratory." *Proc., AAPT,* Vol. 27 (1958) pp. 17-34.
30. HVEEM, F. N., ZUBE, E., and SKOG, J., "Proposed New Tests and Specifications for Paving Grade Asphalts." *Proc., AAPT,* Vol. 32 (1963) pp. 271-327.
31. TRAXLER, R. N., "Relation Between Asphalt Composition and Hardening by Volatilization and Oxidation." *Proc., AAPT,* Vol. 30 (1961) pp. 359-377.
32. HALSTEAD, W. J., and ZENEWITZ, J. A., "Changes in Asphalt Viscosities During Thin-Film Oven and Microfilm Durability Tests." *Public Roads,* Vol. 31, No. 11 (Dec. 1961) pp. 211-218.
33. SKOG, J., " 'Setting' and Durability Studies of Paving Grade Asphalts." *Proc., AAPT,* Vol. 36 (1967) pp. 387-420.
34. SCHMIDT, R. L., and SANTUCCI, L. E., "The Effect of Asphalt Properties on the Fatigue Cracking of Asphalt

Concrete on the Zaca-Wigmore Test Project." *Proc., AAPT,* Vol. 38 (1969) pp. 39-64.

35. ROSTLER, F. S., and WHITE, R. M., "Composition and Changes in Composition of Asphalts, 85-100 Penetration Grade." *Proc., AAPT,* Vol. 31 (1962) pp. 35-89.
36. HEITHAUS, J. J., "The Measurement and Significance of Asphaltene Peptization." Div. of Petroleum Chemistry, ACS, Vol. 5, No. 4-A (1960).
37. PARR, W. K., SERAFIN, P. J., and HUMPHRIES, T., "Michigan State Highway Experimental Bituminous Concrete Construction Project." *Proc., AAPT,* Vol. 24 (1955) pp. 125-177.
38. PARR, W. K., and SERAFIN, P. J., "Four Years Test Trends on the Michigan Bituminous Experimental Road." *Proc., AAPT,* Vol. 28 (1959) pp. 295-315.
39. SERAFIN, P. J., "Seven Year Test on Michigan Test Road." *Proc., AAPT,* Vol. 32 (1963).
40. SERAFIN, P. J., KOLE, L. L., and CHRITZ, A. P., "Michigan Bituminous Experimental Road—Final Report." *Proc., AAPT,* Vol. 36 (1967) pp. 582-614.
41. CORBETT, L. W., and MERZ, R. E., "Asphalt Binder Hardening in the Michigan Test Road After 18 Years of Service." *Transp. Res. Record No. 544* (1975) pp. 27-34.
42. "Proposed Methods for Asphalt Composition Analysis." *1978 Annual Book of ASTM Standards,* Part 15 (1978) pp. 1157-1164.
43. ZUBE, E., and SKOG, J., "Final Report on the Zaca-Wigmore Test Road." *Proc., AAPT,* Vol. 38 (1969) pp. 1-38.
44. SIMPSON, W. C., GRIFFIN, R. L., and MILES, T. K., "Correlation of the Micro-Film Durability Test With the Field Hardening Observed on the Zaca-Wigmore Experimental Project." *ASTM STP No. 277* (1959).
45. DAVIS, T. C., and PETERSEN, J. C., "An Inverse GLC Study of Asphalts Used in the Zaca-Wigmore Experimental Road Test." *Proc., AAPT,* Vol. 36 (1967) pp. 1-15.
46. CHIPPERFIELD, E. H., and WELCH, T. R., "Studies on the Relationships Between the Properties of Road Bitumens and Their Service Performance." *Proc., AAPT,* Vol. 36 (1967) pp. 421-488.
47. CHIPPERFIELD, E. H., DUTHIE, J. L., and GIRDLER, R. B., "Asphalt Characteristics in Relation to Road Performance." *Proc., AAPT,* Vol. 39 (1970) pp. 43-60.
48. LEE, D., "Asphalt Durability Correlation in Iowa." *Hwy. Res. Record No. 468* (1973) pp. 43-60.
49. KENIS, W. J., SR., "Progress Report on Changes in Asphaltic Concrete in Service." *HRB Bull. 333* (1962) pp. 39-65.
50. VALLERGA, B. A., and HALSTEAD, W. J., "Effects of Field Aging on Fundamental Properties of Paving Asphalts." *Hwy. Res. Record No. 361* (1971) pp. 71-92.
51. ZENEWITZ, J. A., and WELBORN, J. Y., "Predicting Asphalt Performance." Rep. No. FHWA-RD-76-133 (1975).
52. WELBORN, J. Y., and HALSTEAD, W. J., "Absolute Viscosity as a Specification Control of Bituminous Binders." *Public Roads,* Vol. 31, No. 12 (Feb. 1962) pp. 243-247.
53. WELBORN, J. Y., "National Coordination of Asphalt Research and Development." *Proc., Hwy. Conf. on R&D,* FHWA, Vol. 2 (1965).
54. SISCO, A. W., and BRUNSTRUM, L. C., "The Rheological Properties of Asphalts in Relation to Durability and Pavement Performance." *Proc., AAPT,* Vol. 37 (1968) pp. 448-475. Also *NCHRP Rep. 67* (1969) 45 pp.
55. SANDVIG, L. D., and KOFALT, J. A., "Penetration and Viscosity Functions in Bituminous Concrete." *Proc., AAPT,* Vol. 37 (1968) pp. 584-621.
56. KANDHAL, P. S., SANDVIG, L. D., and WENGER, M. E., "Shear Susceptibility of Asphalts in Relation to Pavement Performance." *Proc., AAPT,* Vol. 42 (1973) pp. 99-125.
57. FABB, T. R. J., Discussion of paper by Kandhal, Sandvig, and Wenger. *Proc., AAPT,* Vol. 42 (1973) pp. 116-124.
58. KANDHAL, P. S., and WENGER, M. E., "Asphalt Properties in Relation to Pavement Performance." *Transp. Res. Record 544* (1975) pp. 1-13.
59. KEMP, G. R., "Asphalt Durability Tests and Their Relationship to Field Hardening." *ASTM STP 532* (1973).
60. PREDOEHL, N. H., and KEMP, G. R., "Durability of Asphalts—Laboratory Test and Field Data Comparison." Calif. DOT, Div. of Hwys., Rep. DOT-TL-3134-17-74-41 (Mar. 1974).
61. ANDERSON, D. I., PETERSON, D. E., and WILEY, M., "Characteristics of Asphalts as Related to the Performance of Flexible Pavements." Utah DOT, State Study No. 925 B (June 1976) 79 pp.
62. LE CLERC, R. V., and WALTER, J. P., "Design and Performance of Asphalt Concrete Bases in the State of Washington." *Transp. Res. Circ. No. 177* (1976) pp. 4-13.
63. SHAH, S. C., "Asphalt Cement Consistency." *Transp. Res. Record 697* (1978).
64. BROWN, A. B., SPARKS, J. W., and LARSEN, O., "Rate of Change of Softening Point, Penetration, and Ductility of Asphalt in Bituminous Pavement." *Proc., AAPT,* Vol. 26 (1957) pp. 66-81.
65. "A Study of the Use of Viscosity-Graded Asphalt Cements in Experimental Sections." Ohio Highway Research, Interim Reports (1970, 1971, and 1972).
66. WILLIAMS, F. M., MCADAMS, M. M., and REDICK, J. S., "A Study of the Use of Viscosity-Graded Asphalts in Experimental Sections of Pavement." Ohio Div. of Hwys., Final Rep. (1975).
67. HAAS, R. C. G., "A Method for Designing Asphalt Pavements to Minimize Low-Temperature Shrinkage Cracking." Asphalt Institute, *Res. Rep. 73-1* (1973).
68. CRAWFORD, R. A., and ANDERSON, D. W., "Pavement Cracking as Related to Asphalt Hardness." South Dakota Dept. of Highways (1968).
69. "Transverse Cracking of Bituminous Pavements." Final Report, South Dakota DOT (1976).

70. BENSON, P. E., "Low Temperature Transverse Cracking of Asphalt Concrete Pavements in Central and West Texas." TTI Report No. 175-2F (1976).
71. NOURELDIN, M. S., and MANKE, P. G., "A Study of Transverse Cracking in Oklahoma Flexible Highway Pavements." *Transp. Res. Record 697* (1978).
72. KANDHAL, P. S., "Low Temperature Shrinkage of Pavement in Pennsylvania." *Proc., AAPT,* Vol. 47 (1978) pp. 73-114.
73. VAN DER POEL, C., "Time and Temperature Effects on the Deformation of Asphaltic Bitumens and Bitumen-Mineral Mixtures." *Soc. of Plastics Eng. J.,* Vol. II, No. 7 (1955).
74. HEUKELOM, W., "An Improved Method of Characterizing Asphaltic Bitumens With the Aid of Their Mechanical Properties." *Proc., AAPT,* Vol. 42 (1973) pp. 67-98.
75. MCLEOD, N. W., "Determination of Pen-Vis Numbers of Asphalt Cements." *Proc., AAPT,* Vol. 41 (1972) pp. 459-468.
76. FROMM, H. J., and PHANG, W. A., "Temperature-Susceptibility Control in Asphalt-Cement Specifications." *Hwy. Res. Record No. 350* (1971) pp. 30-45.
77. CULLEY, R. W., "Relationships Between Hardening of Asphalt Cements and Transverse Cracking of Pavements in Saskatchewan." *Proc., AAPT,* Vol. 38 (1969) pp. 629-659.
78. ANDERSON, K. O., SHIELDS, B. P., and DACYSZYN, J. M., "Cracking of Asphalt Pavements Due to Thermal Effects." *Proc., AAPT,* Vol. 35 (1966) pp. 247-262.
79. ANDERSON, K. O., and SHIELDS, B. P., "Some Alberta Experience with Penetration-Graded Asphalt Cements Having Different Viscosities at 140 F." *Hwy. Res. Record No. 350* (1971) pp. 15-25.
80. MCLEOD, N. W., "A 4-Year Survey of Low Temperature Transverse Pavement Cracking on Three Ontario Test Roads." *Proc., AAPT,* Vol. 41 (1972) pp. 424-493.
81. PFEIFFER, J. P., and VAN DOORMAAL, P. M., "The Rheological Properties of Asphaltic Bitumen." *J. Inst. Pet. Technologists,* Vol. 22 (1936).
82. FROMM, H. J., and PHANG, W. A., "A Study of Transverse Cracking of Bituminous Pavements." *Proc., AAPT,* Vol. 41 (1972) pp. 383-423.
83. BURGESS, R. A., KOPVILLEM, O., and YOUNG, F. D., "Ste. Anne Test Road—Relationships Between Predicted Fracture Temperatures and Low Temperature Field Performance." *Proc., AAPT,* Vol. 40 (1971) pp. 148-193.
84. GAW, W. J., BURGESS, R. A., and YOUNG, F. D., "Road Performance After Five Years and Laboratory Predictions at Low-Temperature Performance." *Proc., CTAA,* Vol. 19 (1974).
85. CLARK, M. F., and CULLEY, R. W., "Evaluation of Air-Blown Asphalts to Reduce Thermal Cracking of Asphalt Pavements." *Proc., AAPT,* Vol. 45 (1976) pp. 530-551.
86. FENIJN, J., and KROOSHOF, R. C., "The Sliding-Plate Rheometer." *Proc., CTAA,* Vol. 15 (1970).
87. GAW, W. J., ET AL., "A Laboratory and Field Evaluation of Air-Blown, Low Viscosity Waxy Asphalts From Western Canadian Crudes." *Proc., CTAA* (1976).
88. GAW, W. J., "The Measurement and Prediction of Asphalt Stiffnesses at Low and Intermediate Pavement Service Temperatures." *Proc., AAPT,* Vol. 47 (1978) pp. 457-494.
89. SCHWEYER, H. E., SMITH, L. L., and FISH, G. W., "A Constant Stress Rheometer for Asphalt Cements." *Proc., AAPT,* Vol. 45 (1976) pp. 53-77.
90. SCHWEYER, H. E., and BURNS, A. M., "Low Temperature Rheology of Asphalt Cements. III. Generalized Stiffness-Temperature Relations of Different Asphalts." *Proc., AAPT,* Vol. 47 (1978) pp. 1-18.
91. SMITH, W., FINN, F., SARAF, C., and KULKARNI, R., "Bayesian Approach Applied to Prediction of Pavement Distress." *Transp. Res. Record 671* (1978) pp. 54-56.

APPENDIX A

INDIRECT METHODS FOR ESTIMATING STIFFNESS MODULUS

METHOD I—VAN DER POEL

The van der Poel method is in the form of a nomograph and provides a convenient method of representing a large number of experimental results on the basis of creep and dynamic loading. The nomograph shown in Figure A-1 enables estimation of the stiffness modulus over a wide range of temperatures and loadings. Only the penetration at 77 F (25 C) and ring and ball softening point are needed to calculate the penetration index (PI). Pfeiffer and van Doormaal developed a nomograph to determine the PI (Figure A-2).

METHOD II—HEUKELOM

Heukelom modified van der Poel's method to provide a better estimate of stiffness modulus when waxy, blown asphalts are encountered. Penetrations at two temperatures on precooled samples and viscosity at two temperatures are plotted on Heukelom's bitumen test data chart. The softening point is corrected and used to establish a corrected PI to determine stiffness using van der Poel's original nomograph. Heukelom's bitumen test data chart is shown in Figure A-3.

METHOD III—McLEOD

McLeod developed another method for estimating asphalt and mixture stiffness moduli using relationships between viscosity at 275 F (135 C) and penetration at 77 F (25 C). The PI is obtained from the chart shown in Figure A-4. The range in PI values was obtained from a large number of tests on asphalts having different temperature susceptibilities. To obtain the pen-vis number (PVN) for any paving asphalt between or somewhat outside the PVN values of 0.0 and −1.5, only the viscosity at 275 F (135 C) or 140 F (60 C) and penetration at 77 F (25 C) are required.

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

X = log viscosity in centistokes at 275 F for the penetration of asphalt "X"

L = log viscosity in centistokes at 275 F for a PVN of 0.0 for the penetration at 77 F of the asphalt represented by "X".

M = log viscosity at 275 F for a PVN of −1.5 for the penetration at 77 F of the asphalt "X"

McLeod indicated that viscosity in poises at 140 F could be used in place of viscosity at 275 F.

McLeod modified Heukelom's nomograph to determine stiffness modulus by using PVN values as shown in Figures A-5 and A-6.

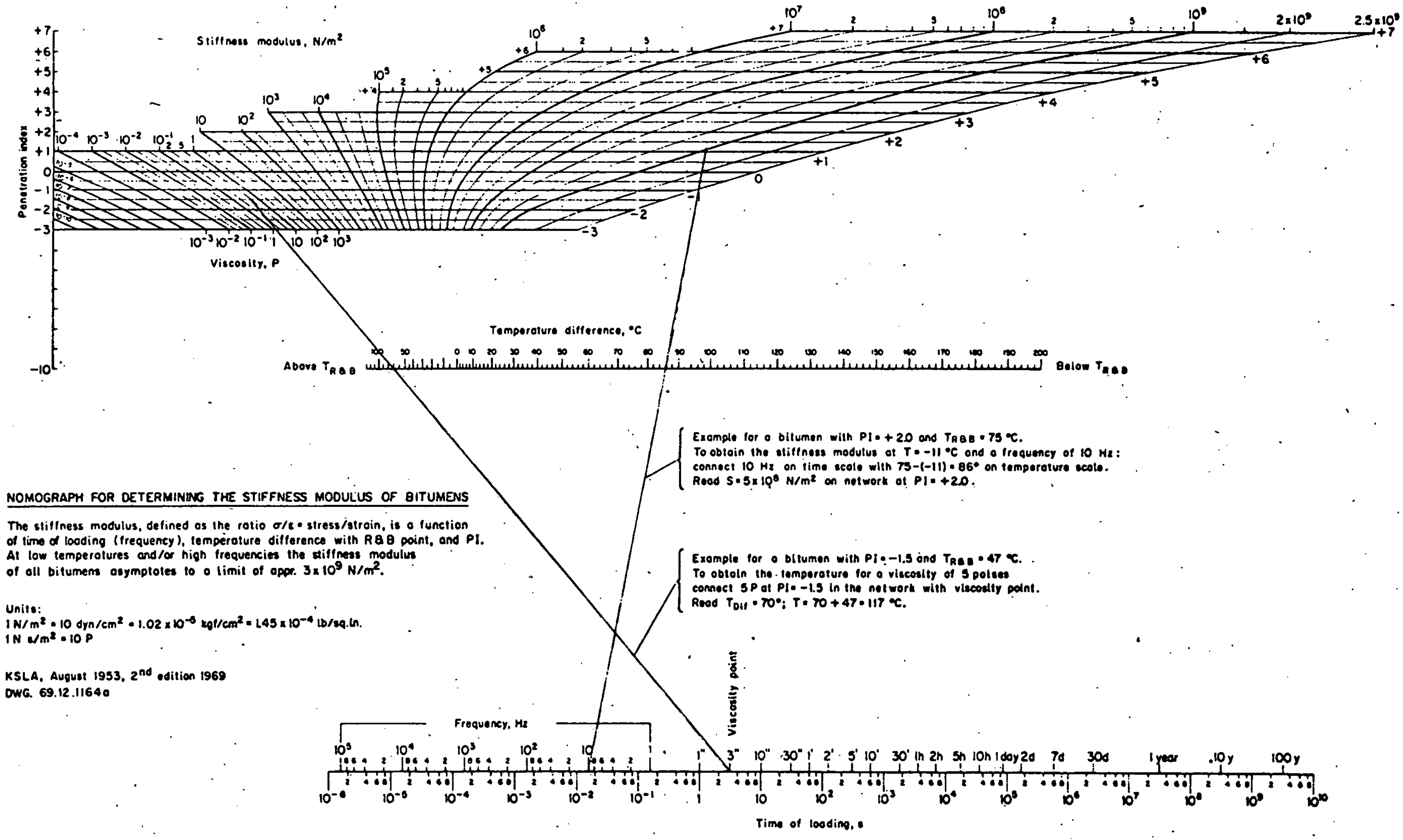

Figure A-1. van der Poel's nomograph for determining stiffness modulus of bitumens. (Source: The Asphalt Institute.)

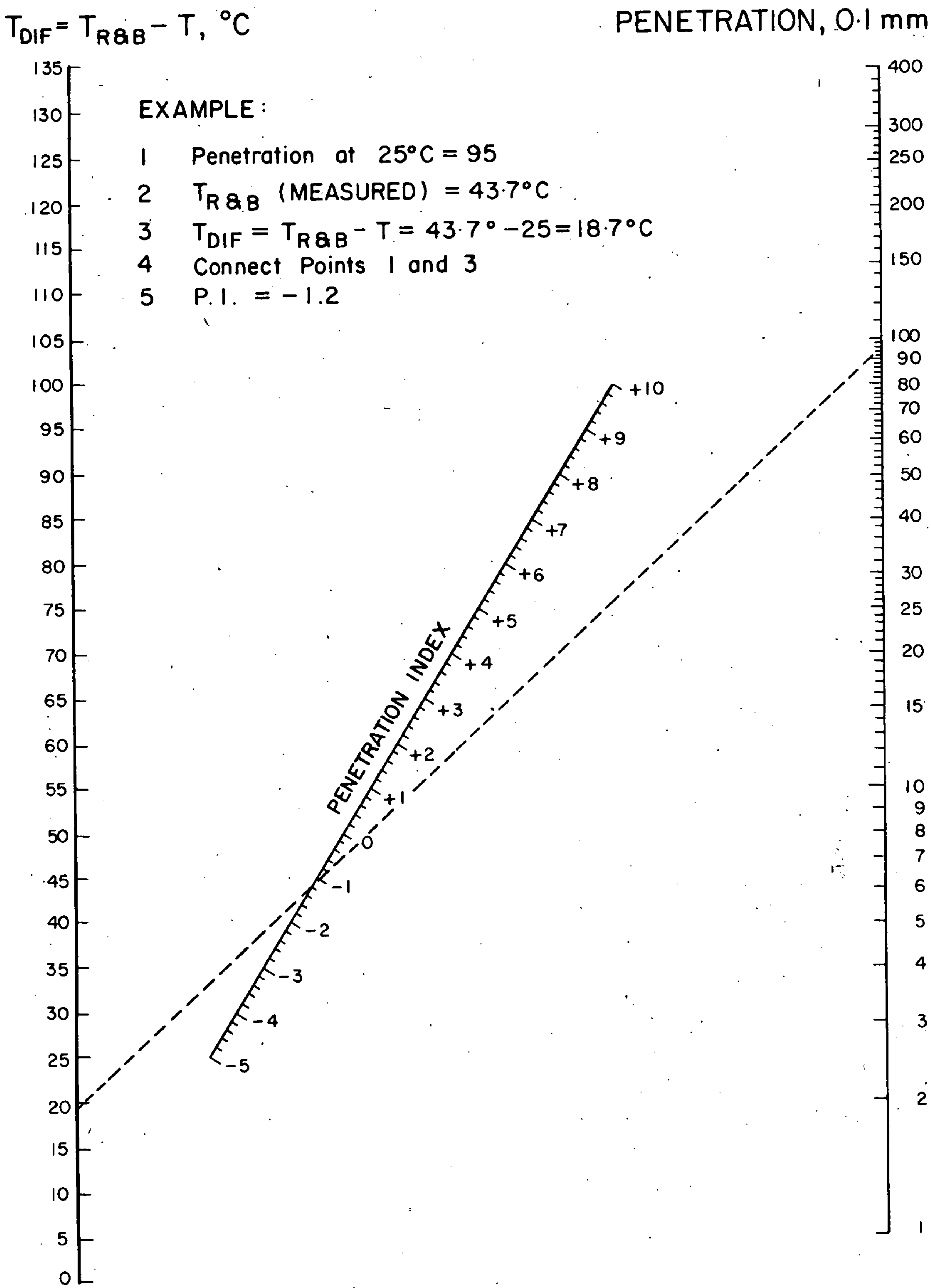

Figure A-2. Nomograph for determining Pfeiffer and Van Doormaal's penetration index.

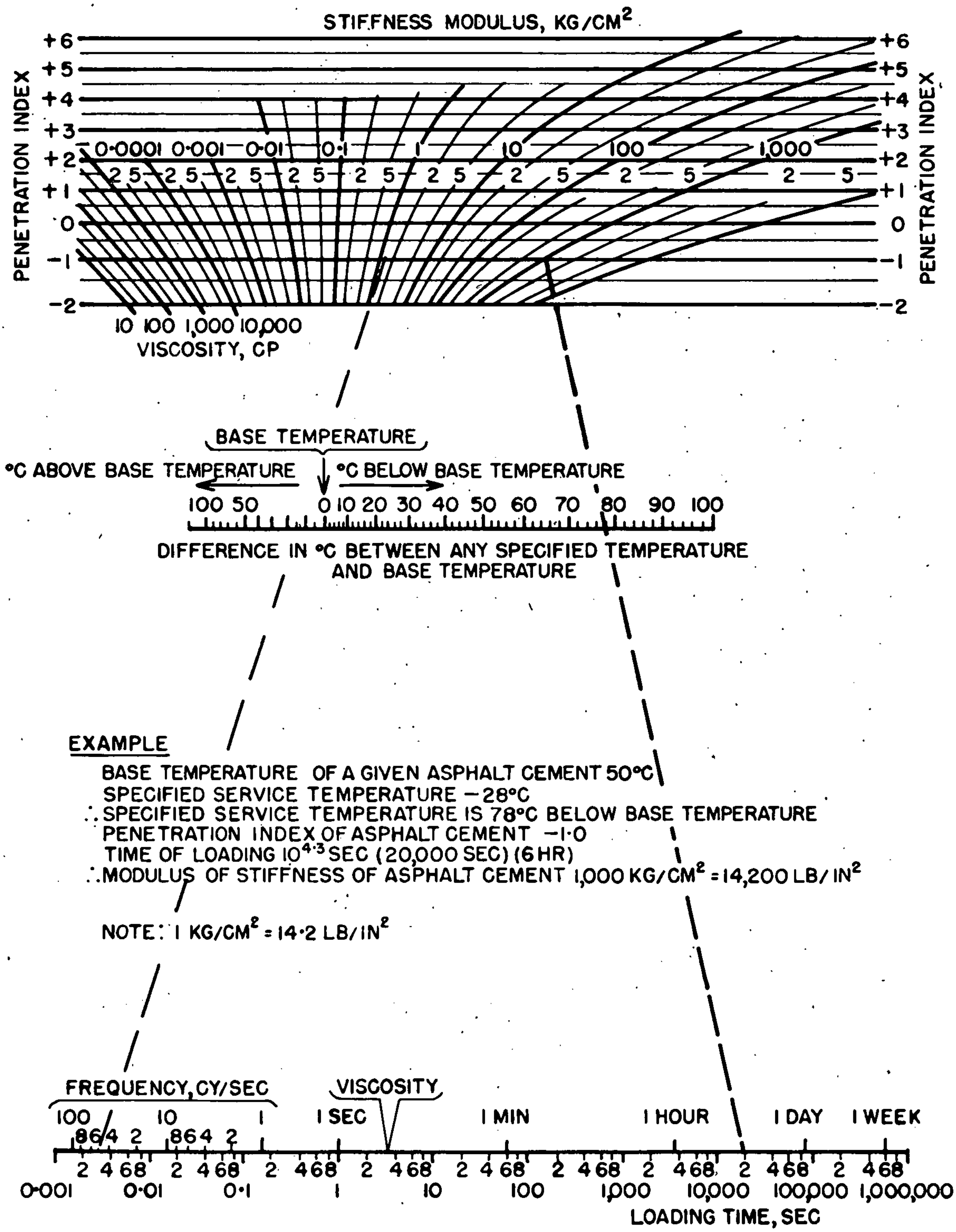

Figure A-3. McLeod's suggested modification of Heukelom and Klomp's version of van der Poel's nomograph for determining modulus of stiffness of asphalt cements.

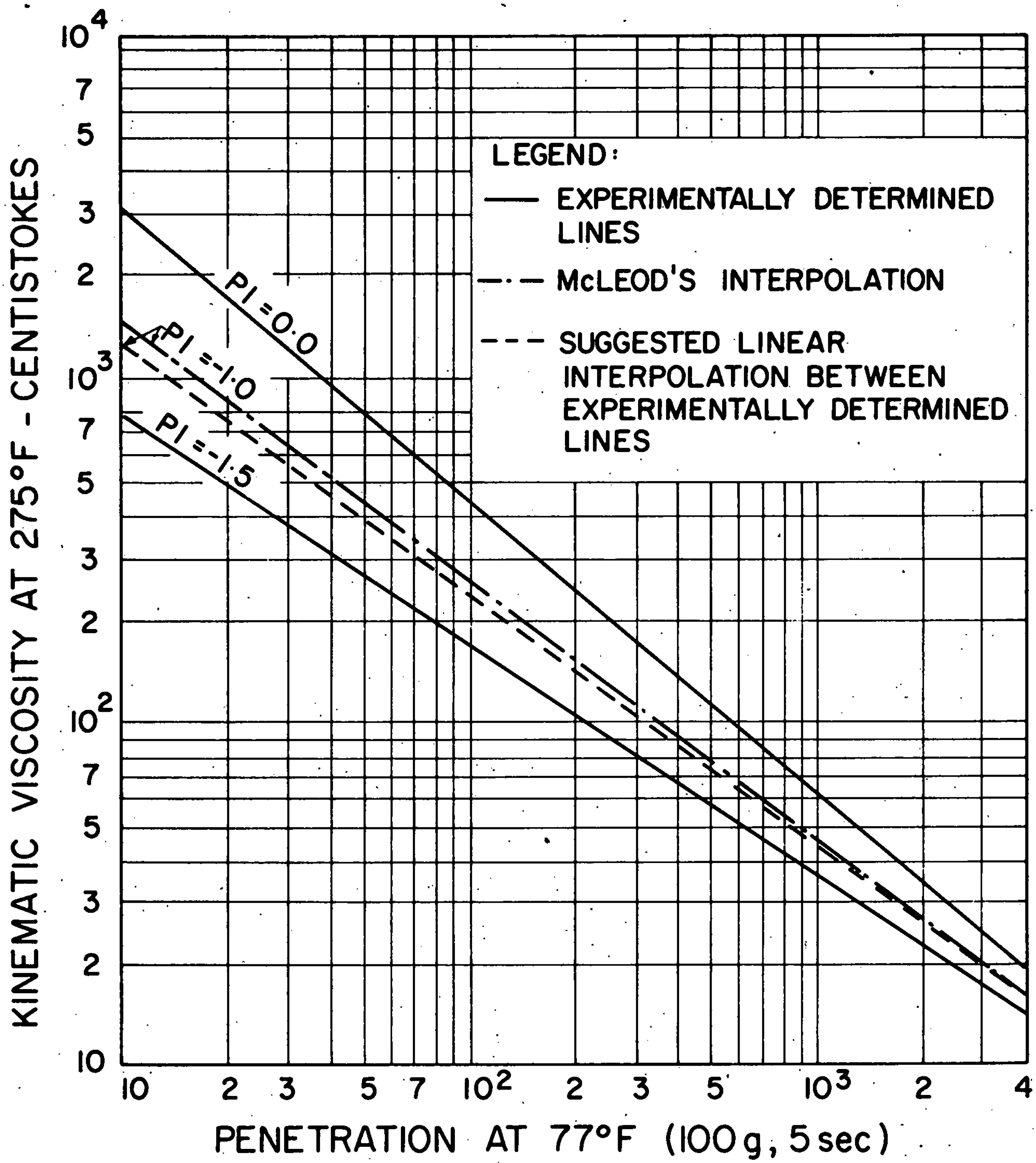

Figure A-4. McLeod's chart for estimating the PI of an asphalt cement.

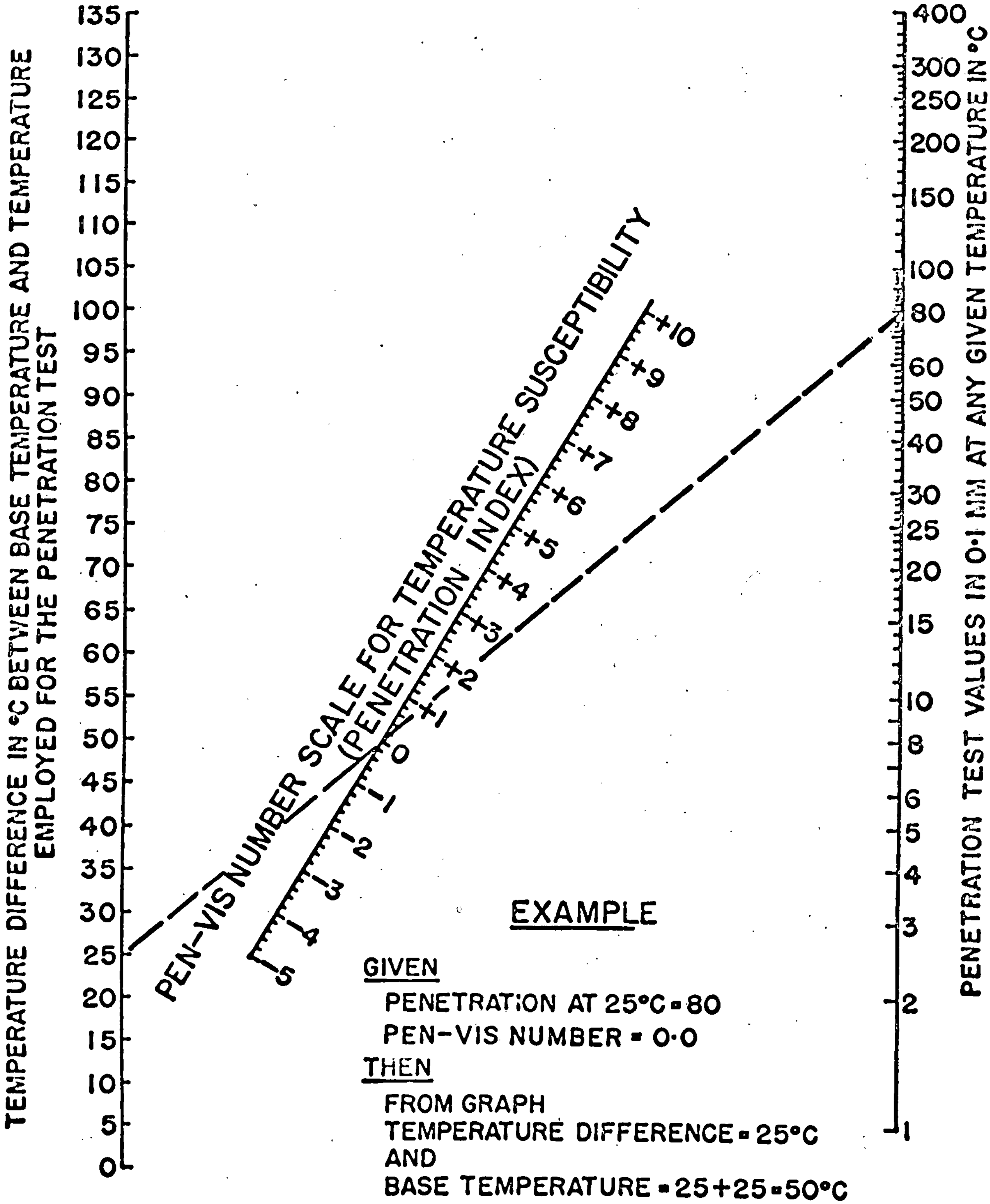

Figure A-5. Suggested modification of Heukelom's version of Pfeiffer and Van Doormaal's nomograph for relationship between penetration, Pen-Vis number, and base temperature.

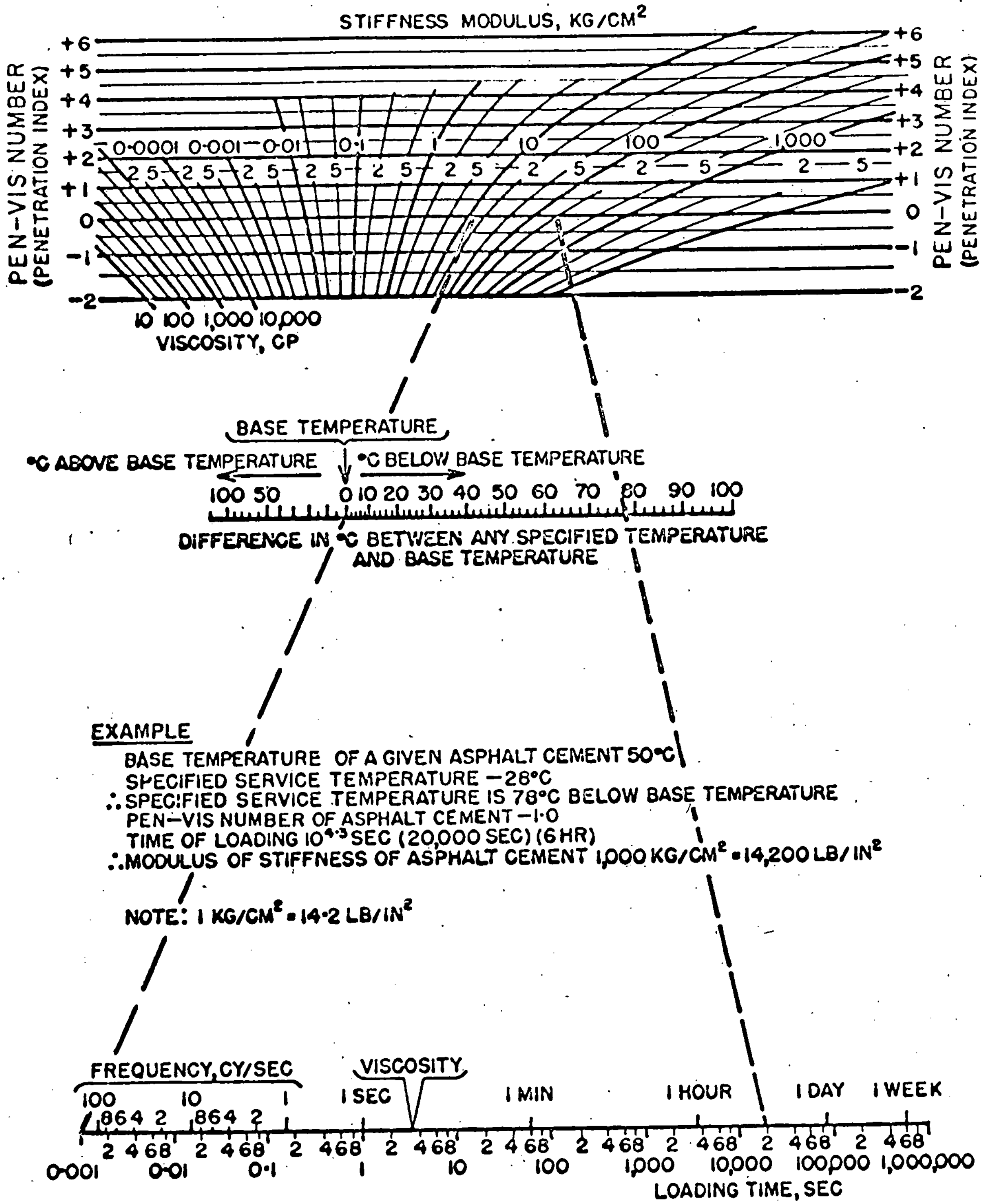

Figure A-6. Suggested modification of Heukelom and Klomp's version of van der Poel's nomograph for determining modulus of stiffness of asphalt cements.

APPENDIX B

SUMMARY OF PAVEMENT PERFORMANCE TESTS

TABLE B-1
CANADIAN TESTS

Source of Test Data	Date Const.	Date Reported	Sections Observed	Distressed Sections	Type of Distress	Cause of Distress	Critical Limit or Range of Asphalt Properties Associated with Distress
Saskatchewan	1963	1969	3	Varied	Transverse cracking	Varied with grade and source of asphalt	Decreased allowable limit for pen & vis
	1966	1969	4	Varied	Transverse cracking	Varied with grade of asphalt	Same as above
Alberta	1966	1971	23	Varied	Transverse cracking	Varied with source and high temperature susceptibility	Min. pen 77 F (25 C) 250 min. vis at 140 F (60 C) 275 Pa•s
Ontario (McLeod)	--	1968	--	Varied	Transverse cracking	Asphalt temperature susceptibility	Minimum pen-vis No. (PVN)
Ontario & Manitoba	--	1971	44	Varied	Transverse cracking	Stiffness modulus too high	Minimum pen-vis No. (PVN)
Ontario (McLeod)	--	1972	9	Varied	Transverse cracking	Stiffness modulus high	Minimum pen-vis No. (PVN)
Ontario (Fromm and Phang)		1972	33	Varied	Transverse cracking	Asphalt source and hardness	Use softer asphalts and lower stiffness modulus
Alberta (Anderson and Shields)	--	1971	30	Varied	Transverse cracking	Asphalts from certain sources	No specific properties
Manitoba--Ste. Anne	--	19	4	2	Transverse cracking	Cracking correlated with asphalt stiffness	Min. stiffness modulus
Saskatchewan (1)	1973	1976	5	0	Transverse cracking	Little difference in cracking	After 24 months no limits set
Manitoba (Gaw et al.) (1)	1971	1977	5	2	Transverse cracking	Low pen of blown asphalts showed higher cracking	No limits set
Ontario (Gaw et al.) (1)	1973	1977	3	0	Transverse cracking	No significant difference in performance	No limits set

(1) Air-blown asphalts used

TABLE B-2

UNITED STATES TESTS

Source of Test Data	Date Const.	Date Reported	Sections Observed	Distress Sections	Type of Distress	Cause of Distress	Critical Limit or Range of Asphalt Properties Associated with Distress
Rader--Ann Arbor, Mich.	1927-1928	1937	(1) 2 UC	1	Severe cracking		13 pen (1 pavement)
Rader--Ann Arbor, Mich.	1926-1929	1938	6 UC	3	Severe cracking	Asphalt hard--40/50 pen used	Cracking related to pen
Hubbard & Gollomb--Eastern U.S.	1935	1937	20 UC	12	Severe cracking	Asphalt hard--50/60 pen used	10-22 pen
Powers--Arizona		1937	12 UC	6	Severe cracking	Asphalt hard	2-6 pen
Raschig & Doyle		1937	18 UC	7	Variable cracking	Asphalt hard	Less than 25 pen - 15 ductility
Miller, Hayden & Vakac		1939	65 UC	23	Variable cracking	Asphalt hard--46/55 pen used	Less than 25 pen
Shattuck	1927-1935	1940	33 UC	16	Variable cracking	Asphalt hard--40/45 pen used	Less than 26 pen - 10 ductility
FHWA (Cuba)	(Not known)	(2)(3)	(3)UC	Varied	Severe cracking and raveling	Asphalt hard	Less than 9 pen
Michigan	1954	1955-1967	6 C	0	Minor raveling in 2 sections	Differences in rate of hardening	Pavements rated good
Zaca-Wigmore Road Test	1954	1969	20 C	2	Alligator and other forms of cracking	Hardness of recovered asphalt	Limits set on TFOT and RTFOT
France	1963	1967-1970	8 C	0	After 11 years some other forms of cracking	Construction problem	Pavements rated good
Germany	1964	1967-1970	8 C	0	After 7 years road resurfaced	Damage from studded tires	Pavements rated good
Iowa--Dah-yinn Lee	1967-1968	1973	8 SC	0	Some transv. and long. cracks	Slight difference in hardening	Pavements rated good
Texas-Traxler		1961	13 SC	0	None reported	--	--
Delaware-Kennis	1958		2 C	0	No distress after 103 months	--	--
Texas-Benson	1964-1968	1976	9 UC		Transverse cracking	Asphalt hard	Control hardness--no limits
California	1964-1969	1973	24 C	0	No problem reported		
Oklahoma		1978	9 UC	4	Transverse cracking	High stiffness modulus	Use failure strain
Pennsylvania--vis & pen graded		1968	18 C	1	Minor raveling - 2 asphalts	Differences in shear susceptibility	Asphalts rated good
Pennsylvania	1978	1978	6 C	2	Extensive transverse cracking	Difference in stiffness moduli	Stiffness moduli less than 275 kg/cm^2 at 20,000 sec loading at lowest pavement temp.
Louisiana--pen & vis study	1970	1978	10 C	0	Minor loss in durability	Vis-graded asphalts in slightly better performance	Vis grading adopted
Ohio--pen & vis study	1968	1971	15 C	0	Minor loss in durability		
FHWA	1954-1956	1970-1975	53 SC	0	Minor cracking & shoving	Variability in asphalt and mix properties	No limit established
Utah	varied	1976	39 UC 20 C	-	Transv. & long. cracking, shoving	Source of asphalt	
South Dakota	varied	1951-1965	172 UC 3 C	126	Transverse cracking	Consistency of asphalt used	Use softer asphalts
American Oil	1954-1956	1969	12 SC	0	Minor cracking & rutting	Aging	--
Virginia	1957	2	3 C	0	None	--	--

(1) UC - uncontrolled, SC - semicontrolled, C - controlled
(2) No published report
(3) 1 road - 12 samples

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