NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 268

INFLUENCE OF ASPHALT TEMPERATURE SUSCEPTIBILITY ON PAVEMENT CONSTRUCTION AND PERFORMANCE

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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INFLUENCE OF ASPHALT TEMPERATURE SUSCEPTIBILITY ON PAVEMENT CONSTRUCTION AND PERFORMANCE

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AREAS OF INTEREST:

PAVEMENT DESIGN AND PERFORMANCE
BITUMINOUS MATERIALS AND MIXES
(HIGHWAY TRANSPORTATION)
(AIR TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
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This report, NCHRP Report 268, and a companion report, NCHRP Report 269, "Paving with Asphalt Cements Produced in the 1980's," will be of special interest and value to individuals responsible for materials testing, mix designs, and construction of asphaltic concrete pavements. The findings of laboratory and field studies on the effects of asphalt cement properties on pavement construction operations and short-term performance are described in this report. These findings indicate that the physical properties of asphalt cements are likely to be more variable today than 20 years ago even though they remain within specification values. However, variations in other material properties and construction practices may mask the influence of this variation on pavement performance. The companion report is a field manual containing suggestions for making adjustments in materials selection, mix design, and construction operations to overcome the variations in asphalt cement properties that have been found to occur. The suggestions in the manual are based on field experience and thus are suitable for immediate implementation.

A strong feeling exists among highway construction and maintenance personnel that asphalt cements used in asphalt paving mixtures have changed; that "Asphalt ain't as good as it used to be!" In addition, many field personnel are of the opinion that current specifications and tests used to select asphalt cements and design paving mixtures do not measure some of the important properties that control field construction and performance of asphalt pavements. The objectives of Project 1-20 were to (1) determine the range or extent of variability in temperature susceptibility of asphalt cements currently being used in road construction; (2) evaluate the effects of the identified variability, in relation to other factors and over a full range of service temperatures, on pavement construction operations and short-term performance of pavements; (3) identify the limits of variability in temperature susceptibility that can be accommodated through application of known asphalt technology by changes in asphaltic concrete construction procedures and mix design considerations; and (4) determine procedures for accommodating or controlling that variability in temperature susceptibility of asphalt cements that cannot be accommodated by known asphalt technology.

To accomplish these objectives, the Texas A&M University researchers conducted an extensive review of available literature on physical and chemical properties and testing methods of asphalt cement. This was followed by the collection and evaluation of data on asphalt cement properties from representative petroleum refineries, the laboratory testing of asphalt cements from refineries considered to produce asphalts that result in varying degrees of construction difficulties, the collection and laboratory testing of asphalt cements and paving mixtures from several construction projects identified as having construction difficulties, and the planning and conduct of a testing program to identify likely construction difficulties based on characteristics of the asphalt cements, paving mixtures, and construction operations. The major results of the research indicate that asphalt cements used on a given construction project may have a greater range of test values and characteristics within specification limits than asphalt cements used on projects in earlier years, primarily because of a wider range of refinery suppliers, crude oil sources, and refining processes. However, with regard to construction problems and pavement performance, the influence of this variability is masked by variations in the characteristics of other materials in the paving mixtures, mix design, and construction operations. Under appropriate design and construction practices, most asphalt cements available will result in acceptable pavement performance. A major question remaining to be resolved concerns how much the performance of asphalt concrete pavements realistically can be improved by better selection and control of the characteristics of the materials used, improved mix design, and modified construction practices.

The research resulted in the publication of two documents: NCHRP Report 268, "Influence of Temperature Susceptibility on Pavement Construction and Performance," and NCHRP Report 269, "Paving with Asphalts Produced in the 1980's." NCHRP Report 268 describes the research effort in response to objectives 1 and 2 listed earlier. NCHRP Report 269 responds to objective 3 as a field manual for implementation of the project findings. In addition, a supplement to NCHRP Report 268 contains extensive data collected and analyzed during the research effort. Copies of the Supplement have been distributed to the program sponsors and are available to other interested persons on written request to the Cooperative Research Programs, Transportation Research Board, 2101 Constitution Ave., NW Washington, D.C. 20418.

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The research reported herein was performed under NCHRP Project 1-20 by the Texas Transportation Institute, Texas A&M University. The principal investigators were Joe W. Button, Associate Research Engineer, Texas Transportation Institute, and Jon A. Epps, Professor of Civil Engineering, University of Nevada at Reno. Other authors of the report are Bob M. Gallaway, Research Engineer and Professor of Civil Engineering, and Dallas N. Little, Associate Research Engineer and Associate Professor of Civil Engineering, Texas Transportation Institute, Texas A&M University.

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INFLUENCE OF ASPHALT TEMPERATURE SUSCEPTIBILITY ON PAVEMENT CONSTRUCTION AND PERFORMANCE

SUMMARY

The overall objectives of the NCHRP Project 1-20 research study were: (1) to determine the range or extent of variability in temperature susceptibility of asphalt cements currently being used in road construction, (2) to evaluate the effects of asphalt cement properties on pavement construction operations and short-term performance of pavements over the full range of service temperatures, (3) to identify the limits of variability in asphalt cement properties that can be accommodated through application of known mixture design techniques, and (4) to determine procedures for accommodating or controlling that variability in temperature susceptibility of asphalt cements that cannot be accommodated by known asphalt technology. The findings of this research are presented in this report, *NCHRP Report 268,* "Influence of Asphalt Temperature Susceptibility on Pavement Construction and Performance," and in a companion report, *NCHRP Report 269,* "Paving with Asphalt Cements Produced in the 1980's." The conclusions reached on the basis of the data collected and analyzed are as follows:

1. Physical properties (including temperature susceptibility) of asphalt cements produced today have the same range of values as those produced in 1964 and those produced immediately prior to the 1965–1973 preembargo period. Data collected from specific refining sources in this study indicated that the physical properties of asphalt cements from selected refineries have changed with time; while asphalts from other refineries have shown no statistically significant change.
2. Limited asphalt cement chemical data are available which define changes with time from a given refinery. Results from a Pennsylvania State University study indicate that on the basis of chemical analyses of available data, the number of potentially poor performing asphalts has increased by about 10 percentage points from 1964 to 1978.
3. Although some asphalt cement properties have changed significantly from a statistical standpoint, it is uncertain if these changes are significant from a pavement construction and pavement performance standpoint. Over a 2-month period, asphalt cements from a given refinery source have changed sufficiently to possibly require the contractor to change plant temperatures 20 to 25 F (11 to 14 C). Depending on the degree of hardening during hot mixing, compaction temperatures may have to be adjusted 25 F (14 C). As an alternative, a harder asphalt may be used.
4. Asphalt cements produced in the post-1976 period have a greater resistance to the thin film oven test (TFOT) hardening, and hence hot mix hardening, than those asphalt cements produced prior to 1977. Asphalts tested in this study and

obtained from 1979 and 1980 production have about the same range of basic properties as measured before-and-after TFOT as those asphalt cements produced in 1977.

5. Temperature susceptibility of asphalt cements is affected very little by artificial aging in the TFOT and rolling thin film oven test (RTFOT). Therefore, aging in an asphalt mixing plant is not expected to significantly affect asphalt temperature susceptibility. The effect of TFOT and RTFOT aging on asphalt consistency is nearly identical over a temperature range from −40 to 275 F (−40 to 135 C).

6. The correlation between asphalt cement properties and field tenderness was, for the most part, masked by variations in aggregate properties and/or construction techniques. However, highly temperature susceptible asphalts and asphalts with high shear susceptibility have been related to tender pavements. These same asphalts exhibit undesirable low temperature characteristics.

7. Asphalts containing less than 10 percent asphaltenes, particularly the softer grades, appear to have a greater probability of producing slow setting paving mixtures. However, an asphalt will manifest itself as slow setting only if the aggregate type and/or gradation is such that a critical paving mixture is produced (even though the aggregate may meet specifications) or possibly if densification of the pavement is inadequate.

8. There is no correlation between asphalt temperature susceptibility and asphaltene content. There is no relationship between asphalt temperature susceptibility and other chemical constituents of asphalts as determined by the Rostler-Sternberg analysis or the Rostler parameter.

9. Asphalt consistency increases with time when asphalts are left undisturbed at 77 F; furthermore, upon heating to 275 F, the asphalt will return to its original consistency. Although this thixotropic property of asphalts is detectable using the standard penetration test or the sliding glass plate in microviscometer at 77 F, it does not correlate well with setting rate in the field.

10. On the basis of the results of this study, asphalt properties alone will not cause a tender mixture during construction. If the aggregate type and/or gradation is such that a critical or tender paving mixture is produced, a highly temperature susceptible asphalt can aggravate the problem at the higher compaction temperatures. When high quality aggregate is employed, asphalt meeting standard specifications can be used to produce a satisfactory paving mixture. High quality aggregate is defined as largely angular, without an excess of sand-size particles, well graded with top size 3/8-in. or greater, and contains sufficient minus No. 200 sieve size particles.

11. The indirect tensile test and the diametral resilient modulus test are much more sensitive to asphalt consistency than either the Hveem or Marshall stability tests. Indirect tensile and resilient modulus tests at 104 F have the potential to identify tender and slow setting asphalt paving mixtures in the laboratory. Based on the guidelines developed in the course of this study, a specifying agency can develop criteria which can be used in the laboratory to avoid tender paving mixtures.

12. Minus No. 200 mesh aggregate (and possibly other fillers) may be used in gravel-type asphalt paving mixtures to increase tensile strength and resilient modulus which would, in all probability, decrease mixture tenderness.

13. The mixture variables that have the greatest influence on resilient modulus and tensile strength of hot mixed asphaltic concrete are asphalt viscosity and filler content.

14. Inasmuch as it is reported that the range in physical properties of asphalt cements is about the same now as it was in 1964 and immediately prior to the 1973 oil embargo, performance problems may be related more to quality control during construction than to the physical properties of asphalt cements. Emphasis should be placed on better training of design and construction personnel, improved inspection

practices by highway departments, and, possibly, tighter materials and construction specifications. Quality control to minimize the probability of mixture tenderness should include aggregate properties as listed in conclusion 10; asphalt grade should correspond with the climatic region; asphalt specifications should address temperature susceptibility; mixture temperature during compaction should be closely monitored; and roller wheel diameter and weight should be appropriate to prevent overstressing of the paving mixture.

On the basis of the foregoing conclusions, it is evident that engineers in selected areas of the United States will be expected to use asphalt cements with properties that change with time. In all probability, the range of asphalt cement properties from a given refinery over a period of time will be no greater than the range of asphalt cement properties currently existing among refineries in the United States. Because a wide range of asphalt cements are currently successfully used in the United States, it is reasonable to assume that technology exists which allows the engineer to successfully make use of a changing asphalt cement from a given refinery.

The remainder of this report gives details of the research effort in Chapters One through Four. Appendixes A through L, the contents of which are as follows, appear in a supplement to this report (see Foreword for availability):

- Appendix A—Results from Statistical Analysis of Asphalt Variability
- Appendix B—Results from Laboratory Testing of Selected Asphalts
- Appendix C—Results from Field-Laboratory Test Program
- Appendix D—Equations for Computing Temperature Susceptibility
- Appendix E—Low Temperature Asphalt Data
- Appendix F—Asphalt Temperature Susceptibility Dependence on Refining Method
- Appendix G—Statistical Analysis of Asphalt Variability by Refinery Source
- Appendix H—Paving at Different Temperatures in Warren and Scappoose, Oregon
- Appendix I—Chromatograms from Gel Permeation Chromatography Tests
- Appendix J—Field Tests in Dickens and Dumas, Texas
- Appendix K—Blunt-Nose Penetrometer Test Results
- Appendix L—Effect of Mixture Variables on the Properties of Asphaltic Concrete

The field manual, entitled "Paving With Asphalt Cements Produced in the 1980's" and published as *NCHRP Report 269,* reviews the changes in asphalt properties which have occurred that can affect the construction and early performance of asphaltic concrete pavements, outlines their potential impacts, and suggests solutions.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Since the 1973 oil embargo, numerous field construction and maintenance personnel throughout the United States have expressed concerns that asphalt cements have changed and that these changes in asphalts have resulted in construction and early life performance problems in asphaltic concrete mixtures. The belief of some field personnel is that the oil companies are taking the "goodies" out of the asphalt and are using them as feedstock for the petrochemical industry. Another belief is that the oil embargo, this country's dependence on foreign crudes, the rapid development of new producing crude oil fields, and economic pressures have led to the production of asphalt cements with reduced performance characteristics. Many field personnel are convinced that the present asphalt specification tests, which are routinely performed, do not identify the important properties that control field construction and pavement performance (*1*, *2*).

As evidence of these concerns, the field engineers cite a general increase in the occurrence of problems such as placement difficulties (tender mixes), excessive displacement under traffic (low stability), thermal cracking, raveling and stripping (water susceptibility) of asphaltic concrete pavements. These problems result in higher maintenance costs, shorter service life, higher life cycle costs, and criticism by the driving public.

Certainly one must accept the opinions offered by these experienced field engineers; however, one must be cautious at the same time. For example, Hveem (*3*) indicated that tenderness problems were evident in California pavements in the 1940's. Field engineers have complained that asphalt "ain't as good as it used to be" as early as the 1930's (*2*, *4*), and asphalt cracking problems were evident early in the history of asphaltic concrete use (*5*). Furthermore, the claims are often vague in nature and are not supported by definitive physical and chemical property data.

Most construction and early performance problems are associated with more than one potential cause. For example, raveling of an asphaltic concrete surface course can be caused by one or a combination of the following factors; poor asphalt quality, low asphalt content, asphalt brittleness, high air void content of mixture, susceptibility to damage by moisture, shear forces due to traffic, and so on. Clearly, all possible causes should be investigated because the properties of the asphalt cement may not necessarily be the primary cause for the recent increase in construction and early performance problems experienced on our nation's highways. Basic societal changes including increased weight and number of vehicles, air quality, and workman safety requirements and the development of equipment to increase production have placed ever changing demands on paving materials.

In an attempt to more adequately define historic changes in asphalt cements, research programs were initiated by The Asphalt Institute (*6*), the Federal Highway Administration (*7*, *8*), and the National Cooperative Highway Research Program (*1*). This report contains a summary of The Asphalt Institute and Federal Highway Administration research programs and documents the NCHRP effort which was performed under Project 1-20. A comprehensive research and development program on asphalt is now being formulated by NCHRP and FHWA because of the increased concern over paving problems and the results obtained from the aforementioned studies.

OBJECTIVES

The main objectives of NCHRP Project 1-20 are as follows:

1. To determine the range or extent of variability in temperature susceptibility of asphalt cements currently being used in road construction.
2. To evaluate the effects of the identified variability, in relation to other factors and over the full range of service temperatures, on pavement construction operations and short-term performance of pavements.
3. To identify the limits of variability in temperature susceptibility that can be accommodated through application of known asphalt technology by changes in asphaltic concrete construction procedures and mix design considerations.
4. To determine procedures for accommodating or controlling that variability in temperature susceptibility of asphalt cements that cannot be accommodated by known asphalt technology.

A Phase I research program satisfied the first objectives by collecting and testing both asphalt cements and asphaltic concrete mixtures from a number of states. Results of the research are reported in detail in Ref. 1 and are included herein. Results of Phase II of the study, which addresses objectives 2 and 3, have been completed and are contained herein in Chapters One through Four (Appendixes A through L are contained in a supplement to this report (see Foreword for availability). A manual, entitled "Paving with Asphalt Cements Produced in the 1980's" and published as *NCHRP Report 269*, contains a review of factors that influence construction problems as well as engineering guidelines that are of immediate use to the practicing engineer in constructing acceptable asphaltic concrete pavements.

The fourth objective of the project was considered of minor importance by the NCHRP Project 1-20 Panel upon review of the Phase I report (*1*). The testing and evaluation plan, therefore, was not performed to satisfy the intent of this objective.

RESEARCH APPROACH

A research program was established to satisfy the objectives of the study. Key elements of the program included:

1. Review of literature to define historic changes in asphalt cement properties.
2. Collection and analysis of asphalt cement data from 23 refineries representing five states in order to establish historic changes in asphalt properties with emphasis on temperature susceptibility.
3. Collection and testing of 16 asphalt cements from 10 refineries. (Those asphalts were selected from refineries noted for producing asphalts having "best" and "worst" and "in between" reputations regarding asphalt-related construction difficulties.)
4. Collection and testing of asphalt cements and asphaltic concrete mixtures from 14 field projects to establish relationships between asphalt cement, asphaltic concrete and pavement construction and early performance problems.
5. Execution of a laboratory testing program to evaluate the effects of asphalt cement properties on pavement construction operations and short-term performance and to identify the limits of variability in asphalt cement properties that can be accommodated through applications of known mixture design techniques.

CHAPTER TWO

FINDINGS

This chapter presents the findings of the study under five major sections as follows: (1) Historic Changes in Asphalt Cements, (2) Asphalt Cement Variability by Refinery Source, (3) Laboratory Testing of Selected Asphalt Cements, (4) Field-Laboratory Test Program and (5) Laboratory Testing of Asphalt Paving Mixtures.

HISTORIC CHANGES IN ASPHALT CEMENTS

Data from several research studies have established historic changes in temperature susceptibility and historic changes in physical-chemical properties of asphalt cement. These studies are identified as:

1. The Asphalt Institute (*6*).
2. Pennsylvania State University (*7, 8*).
3. NCHRP Synthesis 59 (*10*).
4. FHWA-BPR Studies (*11–18*).
5. Asphalt Aging Studies (*19–30*).
6. Department of Energy (*31*).
7. Special State Studies (*32–40*).

References 6, 7, 8, and 11 review the vast majority of data that are available in Refs. 12 through 40. References 6, 7, and 8 contain information that is most pertinent to this study. Comparisons of historic temperature susceptibility data for asphalt cements were made in each of these studies.

Techniques for measuring temperature susceptibility in these studies varied considerably. Temperature susceptibility can be defined as the rate of change of viscosity (or other measure of asphalt consistency) with temperature. Asphalt temperature susceptibility is highly dependent on the temperature range considered and directly related to the type of equipment used to determine asphalt consistency.

Temperature susceptibility of asphalt is an important construction control parameter. Early methods of measuring asphalt temperature susceptibility involved the use of needle penetration devices. Viscosity measuring equipment began to appear in asphalt-related research in the 1920's. Today's specifications often make use of viscosity at 140 and 275 F and penetration at 77 F both before-and-after laboratory aging to control temperature-susceptibility. Methods that have evolved to compare temperature susceptibility of asphalts include the following:

1. Penetration Ratio (*41*).
2. Penetration Index:
   a. Pfeiffer and Van Dormal Method (*41*).
   b. Heukelom's test chart based on penetration (*42, 43*).
   c. Chevron's test chart based on penetration (*43, 44*).
   d. Heukelom's test chart based on viscosity (*42, 43*).
3. Waterman's equation (*45*).
4. Walther's equation (*45*).

Mathematical formulae associated with calculating temperature susceptibility are presented in Appendix D. (Note that all appendixes appear in a supplement to this report; see Foreword for availability.)

A major problem with the methods cited above is the inability to measure low temperature viscosity. Penetration tests have been the only practical method available for measuring low temperature rheology of paving asphalts. However, recent developments have now made possible low temperature viscosity and stiffness measurements possible. Specific devices developed include the following:

1. Schweyer rheometer (viscosity to about 20 F) (*46*).
2. Shell rheometer (stiffness at low temperature) (*47*).
3. Ensley Forced Sphere (viscosity at low temperature) (*48*).
4. Rheometrics mechanical spectrometer (viscosity at low temperature) (*49*).
5. Duomorph (stiffness at low temperature) (*50*).

Limited data are available that define the historical chemical properties of asphalt cements. Chemical data have been collected on asphalt cements from the 1950's using the Rostler-Sternberg method (*51*) or the Corbett method (*52*).

Asphalt Institute Study (*6*)

In 1977, The Asphalt Institute obtained 211 asphalt cement samples from 78 refineries operated by 40 different manufacturers. Physical properties of 68 of the asphalt cements were determined over a wide temperature range and a number of parameters were calculated from these data to describe the temperature susceptibility. Data obtained on the 1977 samples have been compared with asphalt cement samples obtained and tested prior to the 1973 oil embargo. The preembargo samples were obtained in the 1950's and during the period 1965 to 1973.

Several important observations and conclusions were presented by The Asphalt Institute based on the study (*6*). These are listed as follows:

1. Asphalts produced today do not differ substantially from those produced in the past. This applies not only to the conventional properties, used in materials specifications, but also to measurements such as temperature-susceptibility, heat effects, and shear sensitivity.
2. Asphalts, within a given grade, differ substantially in their properties. However, the magnitude of these differences appears to be similar for asphalts manufactured during different time periods.
3. Both the source of parent oils and the method of manufacturer affect the physical properties of asphalt cements. However, because of the wide variation in manufacturing conditions, it is difficult to single out the separate effects of these two factors.

Because of the availability of a large amount of data collected on asphalt cements produced in 1977, the study staff prepared a statistical summary of commonly used parameters to indicate temperature susceptibility. These data are given in Table 1 and will be compared with other data sets found later in this report. A review of the data (Table 1) indicates that the coefficient of variation of these parameters increases as the asphalt cement viscosity increases. In addition, there is more variation in penetration index and pen-vis number than in the viscosity temperature susceptibility.

Pennsylvania State University Study (*7, 8*)

Pennsylvania State University has recently completed an extensive testing and evaluation program to compare both physical and chemical properties of pre- and post-oil-embargo-produced asphalt cements. Statistical techniques were used to identify differences in five different data sets which represent over 700 asphalts produced in 1950's, 1960's, 1977, 1979, and 1981. Those data sets are briefly described in the following. The 1950, 1960, and 1977 data sets were those used in The Asphalt Institute Study.

The FHWA fingerprint file was used to define physical-chemical properties of two data sets. The 1950 FHWA data set contained 311 asphalts, while the 1960 data set contained 58 asphalts (*12*). The 1950 asphalts were collected as part of a series of studies to define the characteristics and performance of penetration graded asphalts (*13–16*). All of the asphalts included in the 1950 data set were commercially produced. The asphalts in the 1960 FHWA data set were samples obtained as part of a cooperative program between the Asphalt Institute and the Federal Highway Administration to develop a viscosity grading specification (*16*). These are the same asphalts as used in Puzinauskas's study previously reviewed and identified as the 1960 data set (*6*).

The third data set (1977) is that reported earlier by The Asphalt Institute (*6*). The fourth data set was obtained and tested by Pennsylvania State University (*7*) and is identified as the 1979 data set. Samples were obtained from 20 state material engineers. More than 100 samples were obtained and tested.

The final data set representing post-embargo asphalts was collected by Pennsylvania State University (*8*) in 1980–1981. Samples of asphalt cement mix from the asphalt plant and pavement cores were obtained on more than 75 construction projects.

Data collected by Pennsylvania State University were compared by use of two-dimensional scatter plots, by comparison of means and standard deviations of data groupings and by the use of advanced statistical techniques. Conclusions presented by Pennsylvania State University researchers are given as follows (*8*).

1. Temperature susceptibility of asphalt cements in the low temperature region has increased over the time period of 1950–1981.
2. When corrected for changes in hardness, the aging index or the increase in hardness on exposure to oven aging has increased over the time period 1950–1981.
3. Except for an increase in temperature susceptibility, it was not possible to measure any asphalt properties that relate to a decrease in asphalt quality. However, this does not mean that such a decrease has not occurred. In any event, the available measurement techniques were not capable of detecting such a change.

Bureau of Public Roads Study (*53*)

In the period 1938–1939, the Bureau of Public Roads obtained 39 samples of 50–60 penetration and 40 samples of 85–100 penetration asphalt cements (*53*). Standard physical property tests were performed on these asphalts together with a series of penetration tests from 32 to 104 F at 9 F intervals. From these data, penetration index (Eq. 1, App. D), penetration ratio (Eq. 3, App. D), and an "exact" penetration temperature susceptibility (Eq. 2, App. D) were calculated and are presented in Tables 2, 3, and 4, respectively. By comparing the data obtained from asphalts produced in the 1938–1939 period with data from the 1954 to 1978 period, it can again be shown that the temperature susceptibility of asphalt cements has increased with time.

Table 1. Temperature susceptibility of asphalt cement tested by The Asphalt Institute (1977).

Parameter	Temperature Range	Statistical Quantity	Asphalt Grade AC-2.5	AC-5	AC-10	AC-20	AC-40
Viscosity-Temperature Susceptibility	140-275°F	$\bar{x}$	3.62	3.57	3.62	3.63	3.71
		s	0.10	0.15	0.17	0.19	0.20
		c_v	2.7	4.3	4.7	5.1	5.3
		R	3.44 to 3.70	3.37 to 4.00	3.41 to 4.05	3.42 to 4.07	3.43 to 3.96
		n	6	16	20	15	11
	77-140°F	$\bar{x}$	3.79	3.75	3.78	3.78	3.81
		s	0.11	0.17	0.17	0.19	0.19
		c_v	2.9	4.6	4.6	5.0	5.0
		R	3.65 to 3.90	3.51 to 4.09	3.55 to 4.07	3.53 to 4.10	3.59 to 4.08
		n	6	16	20	15	11
	39.2-77°F	$\bar{x}$	4.67	4.39	4.29	4.13	3.96
		s	0.17	0.22	0.21	0.19	0.28
		c_v	3.6	5.0	4.8	4.6	7.0
		R	4.52 to 4.99	4.01 to 4.86	3.96 to 4.61	3.81 to 4.51	3.50 4.44
		n	6	16	20	14	10

Parameter (Temp. Range)	Statistical Quantity	Asphalt Grade AC-2.5	AC-5	AC-10	AC-20	AC-40
Penetration Index (39.2-77°F)	$\bar{x}$	-2.08	-1.77	-1.69	-1.40	-1.81
	s	0.47	0.62	0.75	1.06	1.67
	c_v	22	35	44	67	76
	R	-2.81 to -1.56	-2.62 to -0.19	-3.88 to -0.52	-3.86 to 0.17	-3.80 to 0.39
	n	6	16	20	15	11
Pen.-Vis. Number (77-275°F)	$\bar{x}$	-0.66	-0.54	-0.71	-0.69	0.82
	s	0.34	0.47	0.50	0.55	0.62
	c_v	51.1	55.3	70.7	70.2	75.5
	R	-1.00 to -0.31	-1.54 to 0.32	-1.69 to -0.11	-1.83 to 0.10	-1.68 to -0.15
		6	16	20	15	11

$\bar{x}$ = Mean
s = Standard deviation
c_v = Coefficient of variation percent
R = Range
n = Number of readings

Table 2. Distribution of penetration index (PI) of 1938–1939 asphalts.*

Range of PI	Percent Within Range
> 0.3	19.2%
0.3 - 0.0	16.7%
0.0 - -0.3	15.4%
-0.3 - -0.6	20.5%
-0.6 - -0.9	10.3%
-0.9 - -1.2	5.1%
-1.2 - -1.5	12.8%
< -1.5	

No. Samples 78

Mean -0.30

*Computed from asphalt properties presented by Lewis and Welborn (53).

Table 3. Distribution of penetration ratio (PR) of 1938–1939 asphalts.*

Range of PR	Percent Within Range
< 20	0%
20 - 24	0%
25 - 29	15.5%
30 - 34	10.4%
35 - 39	14.3%
40 - 44	20.8%
45 - 49	26.0%
> 49	13.0%

No. Samples 77

Mean 40.8

Coef. Var. 21.8

*Computed from asphalt properties presented by Lewis and Welborn (53).

Table 4. Distribution of "exact" penetration temperature susceptibility (PTS)* of 1938–1939 asphalts.**

Range of PTS	Percent Within Range
> 2.0	0%
2.0 - 1.5	2.6%
1.5 - 1.0	3.8%
1.0 - 0.5	10.3%
0.5 - 0	20.5%
0 - -0.5	29.5%
-0.5 - -1.0	12.8%
-1.0 - -1.5	6.4%
-1.5 - -2.0	5.1%
< -2.0	9.0%

No. Samples 78

Mean -0.30

*"Exact" PTS = Slope of best fit straight line of log penetration versus temperature (penetration test at 100 gm and 5 sec from 32 to 104°F).

**Computed from asphalt properties presented by Lewis and Welborn (53).

Table 5. Asphalt property changes for an AR4000 produced in a western refinery.

Refinery	Date	Properties							
		Original	RTFOT Residue						
		Pen 77°F dmm	Pen 77°F dmm	Visc. 140°F Poise	Visc. 275°F Poise	Ductility cm	Percent Original Pen	VTS 140-275°F	PVN 77-275°F
1-1	05-29-75	80	40	4605	4.95	100	50	3.66	-0.87
	09-11-75	55	33	4928	4.17	100	59	3.82	-1.25
	10-13-75	114	53	4808	6.15	100	46	3.50	-0.30
	03-21-77	125	61	3841	5.40	100	49	3.52	-0.33
	06-14-77	68	36	3933	4.41	100	57	3.69	-1.11
	10-26-77	53	33	4226	3.84	100	62	3.83	-1.36
	06-08-78	57	40	3717	4.65	100	70	3.62	-0.95
	09-08-78	51	31	3939	4.65	100	61	3.65	-1.16
	12-04-78	49	30	4361	4.20	100	61	3.71	-1.32
	04-04-79	45	28	4588	5.07	100	62	3.64	-1.14
	07-17-79	47	29	4363	4.74	100	62	3.67	-1.20
	09-12-79	38	25	4526	4.80	100	66	3.67	-1.30

ASPHALT CEMENT VARIABILITY BY REFINERY SOURCE

The published literature briefly reviewed above indicates that the physical properties of asphalt cements produced today have the same range of values as those produced in 1964 and during 1965–1973 preembargo period (*54*). Furthermore, statistical techniques have been used to indicate that mean values and the distributions of particular physical-chemical properties have varied over the years on a national and regional scale (*55*). However, published literature contains little information to indicate asphalt cement property variation by refinery source. In order to collect this information, a number of states were visited and asphalt cement physical-chemical property data were collected.

Detailed asphalt test data were obtained from 5 states representing 23 refineries in all regions of the United States. A sample of these data is presented in Table A1, Appendix A. The temperature susceptibility parameters, penetration viscosity number PVN (77–275 F) and PVN′ (77–140 F), and viscosity-temperature susceptibility VTS (140–275 F), were computed using the equations given in Appendix D. These parameters together with penetration and viscosity were statistically analyzed using the Statistical Analysis System (SAS) computer program to determine annual means, standard deviations, and coefficients of variation for each refinery. The three statistics were computed and tabulated over all the years for which data were available. Results of this analysis are given in the tables of Appendix A.

Values of PVN and PVN′ normally vary around zero; coefficients of variation, therefore, become quite large in many instances and, unfortunately, are not useful for comparative purposes. Variability in temperature susceptibility may be determined by observing minimum and maximum values of the different parameters. For viscosity graded asphalts, variability in asphalt temperature susceptibility within a calendar year for a given refinery may be estimated by observing the coefficient of variation of penetration. Results are summarized in the following paragraphs.

Western States

Detailed historical data were collected from one western state which obtains and tests asphalts from several refineries. Most properties were measured on rolling thin film oven (RTFOT) aged asphalts, which is the basis for their specification. Table A1, Appendix A, contains a sample of historical data for an AR 4000 asphalt cement from Refinery 1-1. Selected values from Table A1 are presented in Table 5 which show a considerable range of variability of asphalt temperature susceptibility from this refinery during the past 5 years. This variability in individual asphalt properties is reflected in the annual statistical summaries for Refinery 1-1 in Table A2. Several foreign crudes were used in this refinery during this same period.

Table A2 also gives summaries of historical data for two asphalts studied previously in several research programs. They are commonly called California coastal and California valley asphalts (Refineries 1-2 and 1-4, respectively). Generally, the coastal asphalt shows less variability than that from Refinery 1-1, and the valley asphalt shows still less variability. Refineries 1-2 and 1-4 have fairly constant domestic crude sources.

Rostler-Sternberg chemical analyses for the California coastal and valley asphalts (Table 6) show that little chemical change occurred between 1954 and 1975.

Table A3 gives a statistical summary for each western refinery and each grade of asphalt over all years for which data were obtained. The greater variation of asphalts from Refinery 1-1 is quite evident in this table.

Northwestern States

Summaries of asphalt properties were obtained from two northwestern states which contained only yearly means. These data, along with computed values of temperature susceptibility, are presented in Tables A4 and A5. Since individual test data were unavailable, a statistical evaluation was not performed; however, some observations are noteworthy.

In 1977, Refinery 6-1 (Table A5) exhibited a sizeable increase

Table 6. Chemical analysis of two asphalts from a western state over the period 1960 to 1975.

Asphalt Designation	Year	Rostler-Sternberg Fraction						Rostler Parameter	N/P
		Asphaltene	Nitrogen Base	1st Acidaffins	2nd Acidaffins	Paraffins	Wax		
Valley (Ref. 1-4)	1954	11.6	36.7	17.0	20.9	13.8	0.1	1.55	2.66
	1954	8.1	39.6	16.3	22.8	13.2	-	1.55	3.00
		10.9	41.5	14.2	20.7	12.7	0.7	1.67	3.27
	1967	10.7	39.5	14.1	21.7	14.1	-	1.50	2.80
	1975	12.2	42.0	12.5	21.0	12.3	1.4	1.64	3.41
Coastal (Ref. 1-2)	1954	35.9	20.7	21.6	12.4	9.4	0.8	1.94	2.20
	1954	27.8	27.0	20.9	12.6	11.7	-	1.97	2.31
	1967	24.9	30.6	16.8	9.9	17.8		1.71	1.72
	1975	26.2	26.8	19.2	15.8	12.0	1.0	1.65	2.29

* Asphalt Cements are not the Same Grade

in asphalt temperature susceptibility which significantly decreased the following year but not as low as previous years. The state DOT from which these data were obtained experienced considerable tenderness problems in 1974, 1975, and 1976; however, they had none in 1977 and only a few in 1978 and 1979. The increase in temperature susceptibility in 1977 is shown in Table A5 by Refinery 6-1, which is the same as Refinery 8-2 (Table A4). The data, however, came from a different state's laboratory. Note also that data from both states show notably higher asphalt temperature susceptibilities at this refinery in 1973.

Considering the fact that these values are yearly means, Table A4 shows considerable variability in asphalts from Refineries 8-1, 8-2, 8-4, and 8-10 over the past 8 years. On the other hand, Refineries 8-9, 8-11, and 8-12 have produced asphalts with minimal variation (at least on the average) over the same time period. Data from Refinery 8-3 show one jump in temperature susceptibility in 1973 then settle back to fairly stable values. Without more information, one can only speculate as to the reasons for the variation (or the lack of variation) in temperature susceptibility of asphalts from a given refinery.

Southwestern States

Detailed test data for 1979 were obtained from a southwestern state representing three refineries. Table A6, Appendix A, gives the statistical summary. During 1979 all three refineries showed very little variation in asphalt properties. Refinery 4-1 receives domestic crude from the local area, whereas, Refineries 4-2 and 4-3 receive some foreign crudes.

Limited historical data were available from this state; data consist of yearly penetration ranges for viscosity graded asphalt cements over a period of 11 years. These data are given in Table A7.

In 1972, the AC grading specification replaced the OA (oil asphalt) grading system in this state. Therefore, the data from 1968, 1969, and 1971 (Table A7) are estimates of penetrations for the given AC grades based on comparisons of the OA and AC grading specifications. This is the reason for the sharp increase in penetration range for all asphalts after 1971.

Table A7 shows, generally, a slight increase in penetration at 77 F (25 C) (that is, a decrease in temperature susceptibility) since the adoption of the AC grading specification in 1974. Asphalts from Refinery 4-6 are an exception to this trend.

Table 7 shows that the asphalt produced by Refinery 4-2 experienced a significant increase in asphaltene content sometime between 1959 and 1977. The reason for this change is unknown. Asphalts from the four other refineries show no appreciable changes in chemical composition.

Southeastern States

A large quantity of historical data for AC-20 asphalts were obtained from two southeastern states, which represent 12 different refineries. Test data from the two states cover 5 and 7 years. Yearly statistical summaries of these data for each refinery are given in Tables A8 and A10.

Observation of Table A8 reveals remarkably little variation in asphalt temperature susceptibility for most of the refineries within a given year, particularly when compared to the variation exhibited by the refineries represented in Table A10. At this point, one might question the comparative precision of tests conducted by these two states.

Producer 2-5 is actually a supplier (jobber) who distributes asphalt from a given refinery. Until January 1978, this asphalt was obtained from Refinery 2-3, then it was obtained from Refinery 2-1. Note at this same time the sharp decrease in mean temperature susceptibility and increase in variability of the material from Refinery 2-5 (Table A8). Further results of this change are the rather large variations in properties over all years for which data were obtained (Table A9).

Table A10 shows considerable variability in asphalt properties within a given year as well as changes in variability from year to year for several of the refineries studied. Asphalts from Refinery 5-2 are shown to have a consistently wider range of penetration values. Table A11 reemphasizes the consistent variability of this asphalt.

Table 7. Chemical analysis of a southwestern state's asphalts sampled from 1947 to 1977.

Refinery	Grade	Year	Rostler-Sternberg Fraction: Asphaltene	Nitrogen Base	1st Acidaffins	2nd Acidaffins	Paraffins	Wax	Rostler Parameter	N/P
4-2	OA-90	1947	4.7							
	OA-135	1947	4.7							
	OA-230	1947	4.4							
	OA-90	1956	6.2				8.8	+	0.90	
	OA-90	1959	2.5	30.2	25.4	29.3	12.6	-	1.33	2.40
	AC-3	1977	10.0	22.0	17.4	33.1	17.5	Sl. ICE	0.78	1.26
	AC-5	1977	12.2	24.2	17.2	31.0	15.4	Sl. ICE	0.89	1.57
	AC-10	1977	12.5	25.5	17.7	31.7	12.6	Sl. ICE	0.98	2.02
	AC-20	1977	14.8	29.3	16.0	30.9	9.0	+ICE	1.14	3.26
4-3	OA-90	1947	24.2							
	OA-135	1947	23.4							
	OA-230	1947	22.2							
	OA-90	1956	23.2	14.5	23.5	28.2	10.6	+	0.98	1.37
	OA-135	1956	21.4	15.1	25.3	27.0	11.2	Sl. RT	1.06	1.34
	OA-90	1959	18.8	20.0	14.9	28.9	17.4	-	0.75	1.15
	OA-135	1959	11.0	27.2	16.8	28.7	16.3		2.60	1.67
	AC-5	1977	22.4	19.7	16.8	27.6	13.5	Sl. ICE	0.89	1.46
	AC-10	1977	20.7	19.7	17.5	28.0	14.1	Sl. RT	0.88	1.40
	AC-20	1977	22.4	19.7	16.8	27.6	13.5	Sl. ICE	0.89	1.46
4-5	OA-90	1956	21.6	15.0	21.1	25.3	17.0	+	0.85	0.88
	OA-135	1956	19.5	19.0	20.8	23.9	16.8	+	0.98	1.13
	OA-90	1959	17.4	26.2	18.6	21.2	16.6	-	1.19	1.58
	OA-135	1959	11.0	22.0	23.6	27.1	16.3	-	1.05	1.35
	AC-3	1977	16.3	23.1	17.4	29.3	13.9	+RT	0.94	1.66
	AC-5	1977	17.3	24.8	17.0	28.9	12.0	+RT	1.02	2.07
	AC-10	1977	18.3	25.8	16.9	27.1	11.9	+RT	1.09	2.17
	AC-20	1977	18.3	29.4	15.9	26.9	9.5	+RT	1.24	3.09
4-9	OA-90	1956	7.5				5.7	+		
	OA-135	1956	6.1	←51.2→		35.2	7.5	+RT	1.20	
	AC-3	1977	6.7	←86.2→			7.1	+ICE		
	AC-5	1977	4.7	←89.6→			5.7	+RT		
	AC-10	1977	5.4	←89.6→			5.0	Sl. ICE		
	AC-20	1977	9.1	←86.3→			4.6	+ICE		
4-1	OA-90	1956	26.5	11.5	24.1	27.5	10.4	+	0.94	1.11
	OA-135	1956	24.2	14.9	24.0	25.8	11.1	+RT	1.05	1.34
	OA-90	1959	28.5	13.1	20.8	25.2	12.4	-	0.90	1.06
	OA-135	1959	17.5	22.4	19.5	29.2	11.4	-	1.03	1.96
	AC-3	1977	19.1	15.6	19.0	32.0	14.3	+RT	1.14	1.09
	AC-5	1977	20.9	15.4	20.0	32.9	10.8	+RT	0.75	1.43
	AC-10	1977	22.9	16.4	16.3	35.8	8.6	+RT	0.74	1.91
	AC-20	1977	22.8	21.1	18.3	29.1	8.7	+RT	1.04	2.42

Northeastern States

A vast amount of historical asphalt data were received from a northeastern state which included asphalts from 3 refineries and covered a 13-year time period from 1966 to 1979. Although data were supplied from numerous tests, ten to fifteen tests per year were randomly selected for inclusion in the statistical study. A summary of these data on a yearly basis is provided in Table A12. Table A13 gives a statistical summary of the data over all years for which it was available.

In 1972, state number 3 (Tables A12 and A13) replaced the penetration grading specification with the AC grading specification. No significant changes in asphalt temperature susceptibility or asphalt properties variability appear to be associated with this change.

All three of the refineries exhibit considerable variability in asphalt temperature susceptibility within a given year (Table A12) and, generally, the variability between years is not appreciably greater (Table A13). Refinery 3-2 shows a notable increase in asphalt temperature susceptibility.

A second northeastern state supplied data from eight refineries covering a period from 1972 to 1979. This state used the penetration grading system throughout this 7-year period. The data consist of only penetration at 77 F (25 C) and viscosity at 275 F (135 C) and, therefore, were not included in the computer analysis. However, a yearly statistical analysis of these data was performed and is summarized in Table A14.

Asphalt from Refinery 7-1 shows an increase in temperature susceptibility over the years and considerable variability within most years. Asphalts from Refinery 7-2 and 7-7 exhibited mutually similar temperature susceptibilities with comparatively little variability over the years. Refinery 7-8 historically produces a highly temperature susceptible asphalt and the variability in temperature susceptibility is about average with respect to the others supplied by this state.

Statistical Considerations

Variability of the physical properties of asphalt cements from several selected refineries has been statistically evaluated. Detailed results are presented in Appendix G and summarized in the following.

The Statistical Analysis System (SAS) computer program was used to generate statistics which could be used to determine if there was a statistically significant variability in the temperature susceptibility of asphalts with time. The variability of physical properties of asphalts from 17 refineries located throughout the United States was determined on a year to year basis, while within year variability was evaluated on six refineries located in the west and southwest. Results indicate that the temperature susceptibility of asphalts from a large number of refineries have changed with time. It is important to understand that this does not necessarily imply that the temperature susceptibility has changed to such a degree that construction and pavement performance will be affected.

LABORATORY TESTING OF SELECTED ASPHALTS

Asphalt cements were collected and tested in the laboratory to define temperature susceptibility. Asphalts were obtained from refineries that produce asphalts having "best" and "worst" as well as "in between" reputations regarding asphalt-related construction difficulties. Asphalts were selected (in most cases) from refineries which use fairly constant domestic crude sources. Thus the data from the study will likely be applicable for a number of years. The test results provide an indicator of the range in temperature susceptibility of asphalts currently available to the user and define a general relationship between temperature susceptibility and pavement construction difficulties.

Description of Materials

Sixteen asphalt cements of various grades were obtained from 10 different refineries. Table 8 gives information on these asphalts including refinery code, grade, production process, crude source, crude type, market area, user comments pertaining to the asphalt's general performance history with particular emphasis on pavement construction history and a tenderness rating. The tenderness rating is based on a scale from 0 to 5; zero indicates that tenderness or slow setting problems are not normally associated with the asphalt, and five indicates that these problems are always associated with the asphalt. (Details are given in App. L).

Nine of the 10 refineries sampled obtain crude from different parts of the United States, and one obtains some of its crude from Mexico and the Middle East. Asphalts B, C, E, and J have been frequently reported by users to be highly temperature susceptible. Asphalt B is widely used and normally gives acceptable results. Asphalt C has been associated with tender and slow setting mixtures and low early life stability by at least two state highway departments. Asphalts from the producer of Asphalt J experienced a notable increase in temperature susceptibility in 1974 (*56*) and began to obtain a reputation for tender and slow setting mixtures. Asphalts from the producer of Asphalt L are reputed by users to be "some of the best available."

Several of the asphalts tested in this task of the study were produced by refineries whose variability of asphalt properties with time was studied and reported previously.

Test Program on Asphalt Cements

Laboratory tests included the determination of viscosity and penetration as a function of temperature and ring and ball softening point. These tests were performed on all the asphalts before and after the thin film oven test (TFOT) and on selected asphalts after the rolling thin film oven teset (RTFOT). Selected asphalts (before and after oven aging) were subjected to further viscosity testing at temperatures down to −50 F (−46 C). In addition, the following tests were performed on selected asphalts: Asphaltene settling test, chemical composition, penetration as a function of time, viscosity (using sliding glass plate microviscometer) as a function of time, and gel permeation chromatography (GPC).

The Schweyer rheometer (*57*) was used to measure viscosity at 77 F (25 C) and 32 F (0 C). Viscosity at various temperatures ranging from 32 F (0 C) to −50 F (−46 C) were measured using the Rheometrics mechanical spectrometer (RMS).

The RMS was originally designed for polymer research. Theory and operation of this instrument has been described in several publications (*58, 59*). Pink et al. (*49*) were first to publish test results on asphalt using the RMS. Based on their work, rectangular torsion was selected as the test geometry for the work described herein. Rectangular asphalt cement tests specimens, 2.5 × 0.5 × 0.1 in., were molded and kept on ice until ready for testing. A specimen was clamped on each end, placed inside a small environmental chamber and subjected to an oscillating torsional load. Frequency of the torsional load was constant at 6.28 radians per second during all tests. At the start of the test, the temperature was about 32 F (0 C). After the rheology parameters were measured at a given temperature and recorded (which was done automatically by a preprogrammed computer) the specimen temperature was lowered by about 10 F (6 C) and the procedure was repeated until the temperature reached approximately −60 F (−50 C) or until the specimen failed. During each test, induced strain was initially adjusted to 0.03 and then changed to 0.01 to prolong specimen life, as the test temperature decreased or as specimen stiffness increased.

Test Results and Discussions

Asphalt Properties

Data presented in Tables 9 and 10 have been plotted on several figures originally developed by Puzinauskas (*54*). This facilitates a comparison between the data developed in this study and that developed by Puzinauskas (*54*) for asphalts produced up to 20 years ago.

Table 8. Information on asphalt tested.

Asphalt Code	Grade	Refinery	Production Process	Crude Source	Crude Type	Market Area	User Comments	Tenderness Rating
A1	AC-5	East Texas				East Texas		2.0
A2	AC-10	(Same as Refinery 4-5, Table A7)	Vacuum Reduction	East Texas	Fairly Heavy Sour	Arkansas N. Okla.	Not normally a problem asphalt From 1976 production	1.5
A3	AC-20							1.0
B1	AR1000	California						3.0
B2	AR2000	(Same as Refinery 1-4, Table A2)	Vacuum Reduction	San Joaquin Valley, Calif.	Napthenic Low in Asphaltenes	Western United States	Highly temperature susceptible Low volatility, low in asphaltenes Widely used on West Coast	2.5
B3	AR4000							1.5
C	AR 2000	New Mexico	—	Four Corners area of Arizona New Mex. Colorado Utah	Light Paraffinic Low in Asphaltenes	N. New Mexico S. Colo. S. Utah Arizona	Causes construction difficulties Sets slowly Performs well once set up Very small production Excellent in certain blends	4.5
D	AC-20	Illinois (Same as Refinery 2-3, Table A8)	Vacuum Flashed Residue, Air Blown & Blended	West Texas, Mexico, Mid-East	Mixed Sour Rel. Light	East Central United States	Not a problem asphalt	1.0
E	AR 2000	Oregon (Same as Refinery 6-2, Table A5)	—	—	—	—	Highly temperature susceptible Has produced tender paving mixtures	4.0
F1	AR 4000W	Wyoming (Same as Refinery 6-5, Table A5)	Vacuum Reduction	Bighorn Basin North-western Wyoming	Fairly Heavy	Colorado Washington Idaho Wyoming	Not normally a problem asphalt Blamed for tenderness on one job	2.0
F2	AC-20	Wyoming (Same as Refinery 6-5, Table A5)	Vacuum Reduction	Bighorn Basin North-western Wyoming	Fairly Heavy	Colorado Washington Idaho Wyoming	Not normally a problem asphalt This supposedly solved above mentioned isolated tender job (slightly harder grade)	1.0
H	AC-10	Texas Panhandle (Same as Refinery 4-9, Table A7	Propane Deasphalting of Flashed Bottoms and Blend Back	Texas Panhandle Area	Fairly Light	Texas Panhandle Oklahoma New Mexico Colorado Kansas	Low temperature susceptibility Generally good performance Minimum winter cracking Sometimes slow setting	3.0
J	85-100 pen	Kansas 1979 Production	Vacuum Reduction	W. Texas New Mexico Wyoming	—	Midwestern U. S.	No problems before 1974 Notable drop in viscosity for this pen grade in about 1974 Tenderness and slow setting since 1974	3.5
K	AR 2000	California (Same as Refinery 1-2, Table A2)	Steam Vacuum Distillation	Santa Maria California Coastal	Very Heavy	Central & Northern California	Low temperature susceptibility High volatility Diesel-like oil is pumped into ground to soften crude to allow recovery	2.0
L1	AC-10	Arkansas	Vacuum Reduction	Mostly Smackover, Arkansas + Other Domestic	Heavy Cyclic Waxy Sour	Arkansas Lousiana E. Texas Miss.	Fairly low temperature susceptibility Well known as exceptionally good asphalt	0.5
L2	AC-20							0.5

The relationship between penetration at 77 F (25 C) and viscosity at 140 F (60 C) is shown in Figure 1. With the exception of asphalt E, all asphalts tested in this study fall within the boundaries originally developed by Puzinauskas (*54*). Asphalt E is a west coast asphalt cement (AR2000) which exhibited tenderness problems during construction. This asphalt has an unusually low viscosity at 140 F (60 C) for its penetration of 60 as measured at 77 F (25 C).

Figure 2 shows the relationship between viscosities at 140 F (60 C) and 275 F (135 C). The broken line in this graph is an approximation of the minimum viscosities at 275 F listed in either ASTM or AASHTO specifications. Variability of the asphalts tested in this study is almost identical to typical asphalts produced up to 20 years ago except for Asphalt H. Asphalt H is produced in the Southwest and has an exceptionally low temperature susceptibility in this temperature range.

Table 9. Properties of original asphalts.

Asphalt Code	Grade	Viscosity			Penetration, dmm			R&B Softening Point °F (°C)
		77°F (25°C), Poises x 10^5	140°F (60°C), Poises	275°F (135°C), Poises	77°F (25°F) 100 gm @ 5 sec	39°F (4°C) 100 gm @ 5 sec	39°F (4°C) 200 gm @ 60 sec	
A1	AC-5	3.5	494	2.48	176	22	50	107 (41)
A2	AC-10	10.3	1218	3.6	106	14	34	116 (47)
A3	AC-20	35.0	2363	4.0	58	5	16	124 (51)
B1	AR1000	3.2	556	1.3	131	8	38	105 (41)
B2	AR2000	8.3	1037	1.8	85	5	22	112 (45)
B3	AR4000	21.0	2142	2.4	50	1	8	120 (49)
C	AR2000	6.5	554	1.89	111	5	26	110 (43)
D	AC-20	37.0	2140	3.99	58	6	19	126 (52)
E	AR2000	24.0	736	1.83	60	4	14	124 (51)
F1	AR4000	9.2	1571	3.55	80	8	23	116 (47)
F2	AC-20	12.5	1717	3.47	75	7	25	118 (48)
H	AC-10	8.5	1124	5.33	106	8	24	116 (47)
J	85-100	10.5	780	2.25	93	7	27	116 (47)
K	AR2000	3.6	810	2.57	143	18	52	111 (44)
L1	AC-10	8.5	1036	3.2	115	11	30	108 (42)
L2	AC-20	14.0	1705	3.6	80	9	21	121 (49)

Table 10. Asphalt properties after TFOT and RTFOT.

Aging method	Asphalt Code	Viscosity			Penetration		R&B Softening Point, °F (°C)	Percent Loss
		77°F (25°C), Poises x 10^5	140°F (60°C), Poises	275°F (135°C), Poises	77°F (25°C) 100 gm, 60 sec, dmm	39°F (4°C) 200 gm, 60 sec, dmm		
Thin Film Oven Test (TFOT)	A1	5.5	1067	3.2	113	41	115 (46)	0.00
	A2	24	2712	4.9	67	27	125 (52)	0.01
	A3	82	6368	5.8	33	9	136 (58)	0.06
	B1	7.9	900	1.6	85	21	111 (44)	0.74
	B2	16	1338	2.2	58	12	117 (47)	0.46
	B3	46	3210	3.0	33	6	128 (53)	0.44
	C	13	1064	3.5	64	12	122 (50)	0.64
	D	92	5236	5.3	37	14	135 (57)	0.07
	E	44	1534	2.7	29	9	128 (53)	0.56
	F1	35	4324	5.3	45	18	130 (54)	0.23
	F2	36	4463	5.2	43	16	130 (54)	0.22
	H	15	1823	7.4	73	--	124 (51)	0.00
	J	24	1593	3.8	52	12	122 (50)	0.04
	K	28	1946	4.9	65	23	128 (53)	1.55
	L1	20	1875	3.9	70	19	124 (51)	0.01
	L2	52	4614	5.8	48	11	130 (54)	0.03
Rolling Thin Film Oven Test (RTFOT)	A2	22	2497	4.8	65	27	126 (52)	0.14
	B1	8.9	965	1.6	81	18	114 (46)	1.10
	B2	19	1700	2.3	57	12	122 (50)	0.68
	B3	68	3653	3.2	31	6	129 (54)	0.57
	F1	27	3413	5.2	47	16	127 (53)	0.17

Figure 3 relates penetrations measured at 77 F (25 C) and 39.2 F (4 C). Values at both temperatures were ascertained using a needle weight of 100 grams for a duration of 5 sec. Values for the asphalts tested in this program fall within or very close to the boundary lines established by Puzinauskas (*54*). This indicates little or no change in variability of asphalt temperature susceptibility in recent years. Interestingly, a line connecting the three asphalts from source A and a line connecting those from source B encompass all asphalts tested in this program except Asphalt C.

Bitumen Test Data Chart

Plots of the data for the 16 asphalts tested in this study are plotted on Heukelom's bitumen test data chart (*60*) and presented in Figures B1 through B16, Appendix B. These charts provide a convenient method to graphically present basic asphalt properties. The slope of the best fit straight lines through the viscosity data and the penetration data indicates the degree of asphalt temperature susceptibility in the two temperature ranges. Steeper slopes indicate a greater temperature susceptibility. The

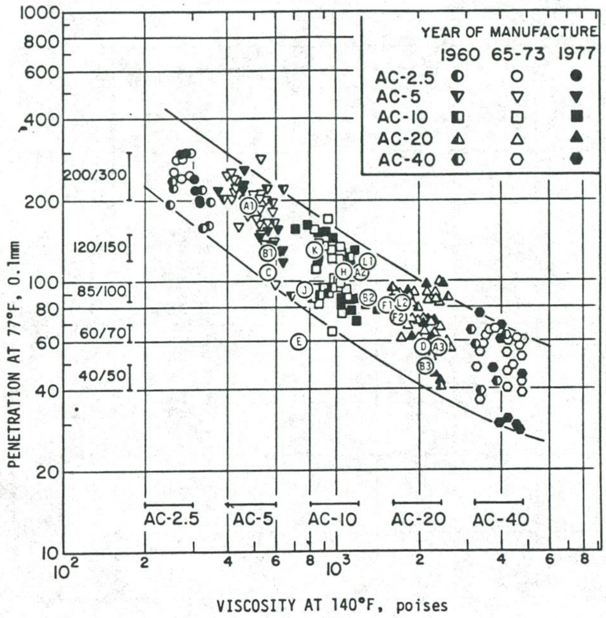


Figure 1. Relationship between viscosity at 140 F (60 C) and penetration at 77 F (25 C) for asphalt cements. (After Puzinauskas, **54***)*

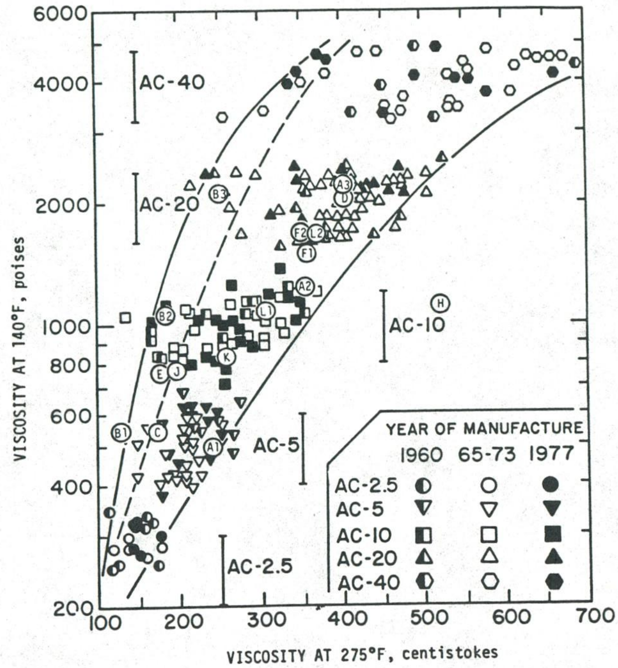


Figure 2. Relationship between viscosity at 140 F (60 C) and 275 F (135 C) for asphalt cements. (After Puzinauskas, **54***)*

uppermost intercept (where penetration is equal to one) in the penetration portion of the plot is an indicator of low temperature performance; poorer low temperature performance would be expected when these intercepts occur at higher temperatures. Relative asphalt hardening upon oven aging is readily apparent by observing the distance between the solid and dashed lines on these figures.

Comparison between the bitumen test data charts to determine relative temperature susceptibility of the asphalts is rather awkward. However, careful observation reveals that, at temperatures between 77 F (25 C) and 275 F (135 C), Asphalt H exhibits an unusually low temperature susceptibility; whereas, Asphalts B1, B2, B3, C, E, and J exhibit abnormally high temperature susceptibilities. Asphalts A1, B2, B3, C, and H show a significant increase in temperature susceptibility in the low temperature (penetration) range. About one-half of these asphalts show slight variations in temperature susceptibility after oven aging. According to Heukelom (*43*), when the penetration plot and the viscosity plot for a given asphalt are parallel and the penetration plot is offset toward lower penetrations, the asphalt contains wax. Asphalts D, E, and F appear to fall in this category.

Effects of Oven Aging

Table 11 shows that asphalts A2 and F1 were hardened more by the TFOT and that asphalts B1, B2, and B3 were hardened more by the RTFOT. However, the differences in hardening by the two methods are not large. Loss on heating is included in Table 10. Viscosity ratios and retained penetrations have been

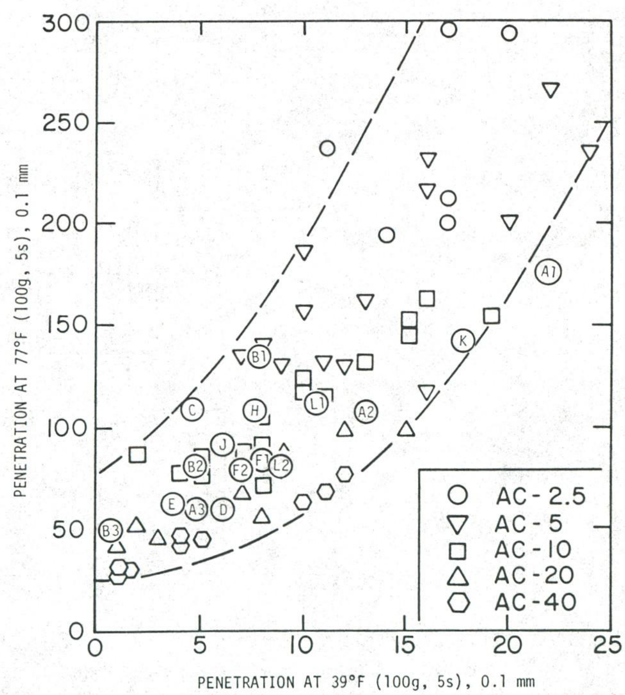


Figure 3. Relationship between penetration at 77 F (25 C) and 39.2 F (4 C) temperature. (After Puzinauskas, **54***)*

Table 11. TFOT and RTFOT hardening indexes.

Asphalt Code	Thin Film Oven Test (TFOT) Visc. Ratio* 77°F	Visc. Ratio 140°F	Visc. Ratio 275°F	Retained Penetration, Percent 77°F	Rolling Thin Film Oven Test (RTFOT) Visc. Ratio 77°F	Visc. Ratio 140°F	Visc. Ratio 275°F	Retained Penetration, Percent 77°F
A1	1.57	2.16	1.29	64				
A2	2.33	2.23	1.36	63	2.13	2.05	1.33	61
A3	2.34	2.69	1.45	57				
B1	2.47	1.62	1.23	65	2.78	1.74	1.26	62
B2	1.93	1.29	1.23	68	2.29	1.64	1.28	67
B3	2.19	1.50	1.25	66	3.24	1.71	1.33	62
C	2.0	1.92	1.86	58				
D	2.49	2.45	1.33	64				
E	1.83	2.08	1.48	48				
F1	3.80	2.75	1.49	56	2.93	2.17	1.45	59
F2	2.88	2.60	1.50	57				
H	1.76	1.62	1.39	69				
J	2.24	2.04	1.69	56				
K	7.78	2.40	1.91	45				
L1	1.70	1.81	1.20	61				
L2	3.71	2.71	1.61	60				

$^{*}\dfrac{\text{Viscosity of laboratory hardening asphalt at designated temperature}}{\text{Viscosity of original asphalt at designated temperature}}$

computed following both oven tests and are presented in Table 11.

Figure 4 gives the relationship between viscosity at 140 F (60 C) for original and TFOT-treated asphalt cements. The dashed line indicates a tighter grouping of asphalts produced during 1977 as compared to asphalts produced prior to 1977. Asphalts tested in this study also plotted below the dashed line, which suggests that asphalts produced after 1976 have greater resistance to TFOT hardening than those produced earlier. Reasons for these differences are not readily apparent. According to Puzinauskas (*54*), they may be related to factors such as changes in crude oil sources and/or modifications of the manufacturing processes.

Figure 5 shows the effect of the TFOT on penetration at 77 F (25 C). The asphalts originally used to construct this plot were produced in 1977 and resulted in a rather tight grouping bordered by straight lines on a logarithmic scale. Asphalts E and K hardened more than those asphalts produced in 1977 and hence plotted outside the borderlines. Figure 6 provides a comparison between viscosity ratio (heated/original) at 140 F (60 C) and retained penetration at 77 F (25 C). This figure is presented to illustrate the lack of correlation between these two parameters and to show that penetration and viscosity tests will indicate wide variations in heat sensitivity for asphalts produced since 1977.

Figure 7 provides information on the effects of heating on viscosities of asphalt cements at 275 F (135 C). This graph indicates that high temperature viscosities of asphalt are altered substantially by heating. Furthermore, such differences in viscosity may significantly influence the mixing efficiency of asphalt-aggregate mixtures, wetting characteristics of asphalt and capillary absorption of asphalt by aggregates (*54*) and thus affect workability and compaction of paving mixtures. Asphalts C and K, both susceptible to excessive hardening upon heating, plotted just outside the boundaries defined by the 1977 asphalts.

In summary, Figures 4 through 7 show that the asphalts tested in this study have about the same range of basic properties before and after heating as those produced in 1977.

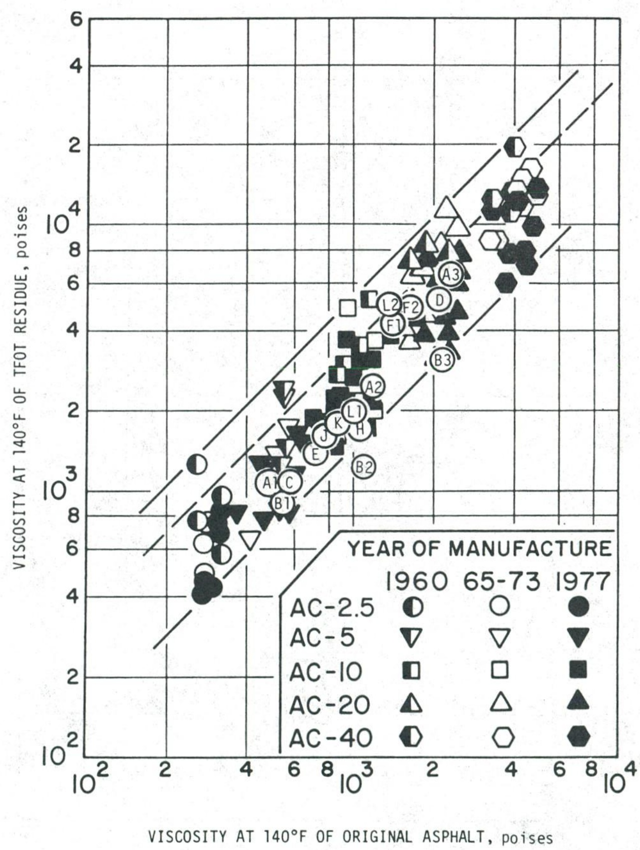


Figure 4. Relationship between viscosity at 140 F (60 C) for original and heated asphalt cements. (After Puzinauskas, **54***)*

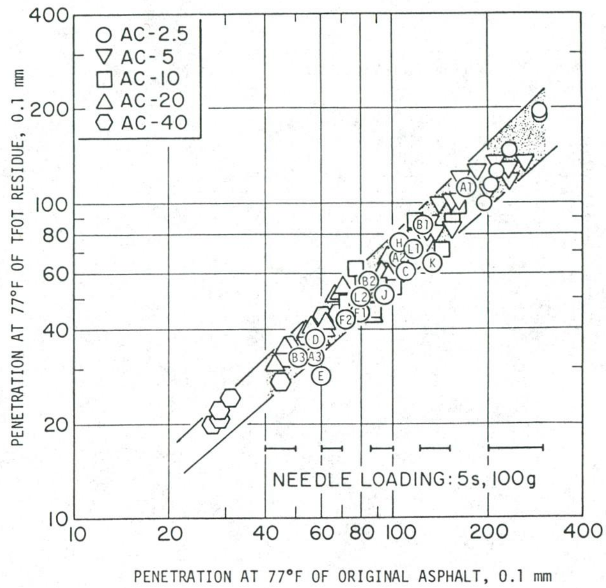


Figure 5. Effect of TFOT heating on penetration at 77 F (25 C) for asphalt cements. (After Puzinauskas, ***54****)*

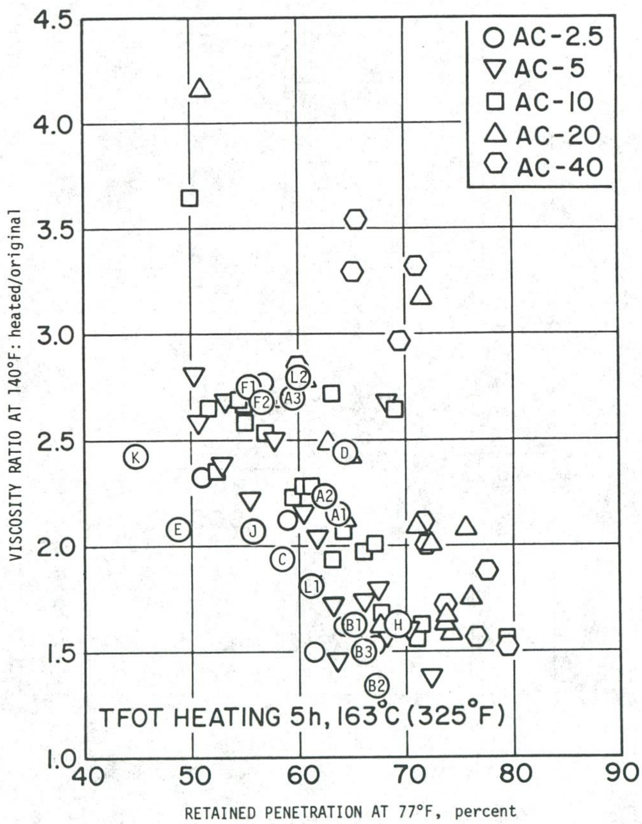


Figure 6. Heating effects on asphalt cements as compared by viscosity and penetration tests. (After Puzinauskas, ***54****)*

Temperature Susceptibility

Seven different methods were used to compute temperature susceptibility of the 16 original, TFOT- and RTFOT-aged asphalts. One additional method was used for the original asphalts. Results of these computations are presented in Table 12. Appendix D contains a list of the formulae used for these computations.

Figure 8 depicts viscosity as a function of temperature for 5 of the 16 asphalts tested. The remaining 11 asphalts would plot within the boundaries created by these asphalts, but were excluded to reduce clutter. Calculations show that Asphalt H has the lowest viscosity temperature susceptibility (Eq. 6, App. D), and Asphalts B1, B2, and B3 have the highest viscosity temperature susceptibility, which is in agreement with slopes of the curves in Figure 8.

Figure 9 depicts penetration as a function of temperature for the asphalts from sources A and B. All tests were conducted with a needle load of 100 grams for a duration of 5 sec. Regarding temperature susceptibility in this temperature range, Asphalts A1, A2, and A3 are "typical," and Asphalts B1, B2 and B3 are quite high. The remaining 10 asphalts will plot between the curves plotted for Asphalts A1 and B3.

Figure 10 relates penetration-viscosity number (PVN) and viscosity-temperature susceptibility (VTS) of 68 asphalts tested by Puzinaukas (*54*) and the 16 additional asphalts tested in this study. Data contained in this figure are based on tests performed at 77 F (25 C) and 275 F (135 C). A fairly good correlation between these two parameters is indicated; however, considerable scatter is also shown. The band enveloping the 16 asphalts

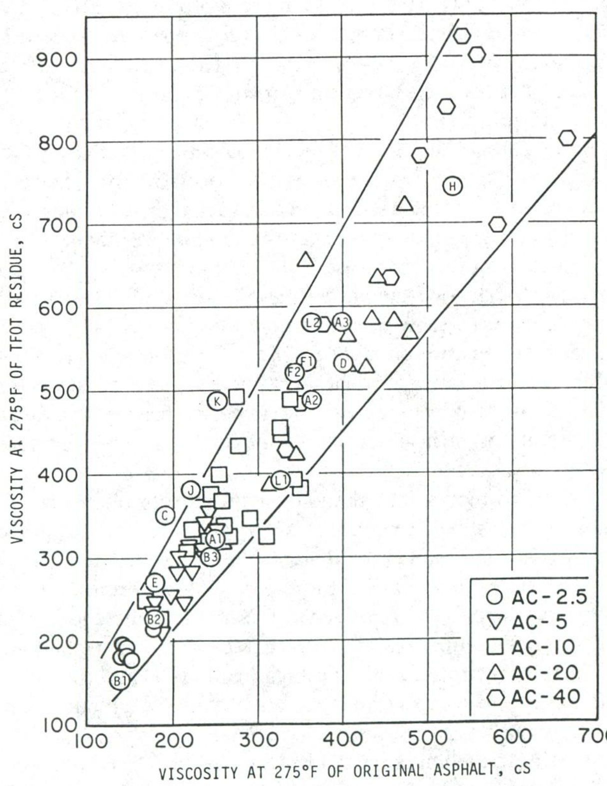


Figure 7. Effect of TFOT heating on viscosity at 275 F (135 C) for asphalt cements. (After Puzinauskas, ***54****)*

Table 12. Temperature susceptibility parameters before-and-after oven aging.

Asphalt Code	Penetration Ratio			Penetration Temperature Susceptibility			Penetration Index**	Penetration Index *		
	Original	TFOT	RTFOT	Original	TFOT	RTFOT	Original	Original	TFOT	RTFOT
A1	28	36	--	0.022	0.022	--	-0.48	+0.09	-0.04	--
A2	32	40	42	0.023	0.022	0.022	-0.30	-0.08	-0.06	-0.01
A3	28	27	--	0.024	0.024	--	-1.51	-0.57	-0.36	--
B1	29	25	22	0.028	0.029	0.027	-2.29	-1.49	-1.61	-1.23
B2	26	21	21	0.028	0.029	0.026	-2.37	-1.44	-1.58	-0.89
B3	16	18	19	0.028	0.027	0.027	-4.05	-1.48	-1.29	-1.29
C	23	19	--	0.026	0.024	--	-2.87	-1.02	-0.61	--
D	33	38	--	0.023	0.023	--	-1.03	-0.31	-0.23	--
E	23	31	--	0.024	0.028	--	-2.11	-0.49	-1.53	--
F1	29	40	34	0.027	0.024	0.025	-1.13	-0.93	-0.39	-0.67
F2	33	37	--	0.025	0.024	--	-1.31	-0.79	-0.49	--
H	23	--	--	0.023	0.022	--	-1.83	-0.08	+0.03	--
J	29	23	--	0.024	0.026	--	-1.84	-0.50	-1.11	--
K	36	35	--	0.022	0.021	--	-1.46	+0.07	+0.26	--
L1	26	44	--	0.027	0.023	--	-1.25	-1.30	-0.08	--
L2	26	46	--	0.023	0.023	--	-0.80	-0.15	-0.24	--

* Computed using formula No. 1, Appendix D

**Computed using formula No. 2, Appendix D

Asphalt Code	Pen/Vis No. (77°F to 275°F)			Pen/Vis No. (77°F to 140°F)			Viscosity-Temp. Susceptibility (140°F to 275°F)		
	Original	TFOT	RTFOT	Original	TFOT	RTFOT	Original	TFOT	RTFOT
A1	-0.30	-0.43	--	-0.62	-0.50	--	3.31	3.43	--
A2	-0.32	-0.37	-0.44	-0.46	-0.36	-0.49	3.39	3.46	3.45
A3	-0.81	-0.83	--	-0.71	-0.57	--	3.57	3.65	--
B1	-1.71	-1.77	-1.78	-0.90	-1.13	-1.13	3.98	3.99	3.99
B2	-1.60	-1.63	-1.58	-0.98	-1.28	-1.06	3.94	3.85	3.91
B3	-1.64	-1.67	-1.63	-1.02	-1.20	-1.16	3.97	3.93	3.93
C	-1.27	-0.89	--	-1.25	-1.37	--	3.61	3.35	--
D	-0.81	-0.85	--	-0.81	-0.59	--	3.53	3.65	--
E	-1.87	-1.90	--	-1.83	-2.03	--	3.77	3.73	--
F1	-0.65	-0.67	-0.66	-0.64	-0.50	-0.66	3.50	3.58	3.51
F2	-0.75	-0.73	--	-0.65	-0.53	--	3.56	3.61	--
H	-0.30	-0.32	--	-0.55	-0.63	--	3.04	2.98	--
J	-1.18	-0.98	--	-1.15	-1.26	--	3.61	3.45	--
K	-0.50	-0.40	--	-0.41	-0.74	--	3.50	3.33	--
L1	-0.40	-0.67	--	-0.50	-0.66	--	3.42	3.51	--
L2	-0.63	-0.48	--	-0.56	-0.34	--	3.53	3.53	--

Asphalt Code	Viscosity-Temp. Susceptibility (77°F to 275°F)			Viscosity-Temp. Susceptibility (77°F to 140°F)			Temperature of Equal Stiffness,* °F(°C)		
	Original	TFOT	RTFOT	Original	TFOT	RTFOT	Original	TFOT	RTFOT
A1	3.65	3.59	--	4.27	3.88	--	-55(-48)	-44(-42)	-35(-37)
A2	3.64	3.62	3.61	4.09	3.90	3.92	-55(-48)	-33(-36)	--
A3	3.78	3.73	--	4.18	3.86	--	-27(-33)	-17(-28)	-36(-38)
B1	4.03	4.06	4.08	4.13	4.20	4.20	-28(-34)	-22(-30)	-22(-30)
B2	4.00	3.99	3.99	4.11	4.23	4.14	-22(-30)	-14(-26)	-17(-27)
B3	3.98	3.98	4.01	4.01	4.08	4.16	-18(-28)	-9(-23)	--
C	3.93	3.69	--	4.49	4.31	--	-33(-36)	-29(-34)	--
D	3.79	3.79	--	4.27	4.05	--	-29(-34)	-22(-30)	--
E	4.17	4.04	--	4.89	4.60	--	-28(-34)	-3(-16)	-20(-29)
F1	3.62	3.64	3.61	3.84	3.75	3.79	-27(-33)	-24(-31)	--
F2	3.69	3.65	--	3.93	3.74	--	-29(-34)	-22(-30)	--
H	3.40	3.33	--	4.06	3.97	--	-63(-53)	-37(-39)	--
J	3.90	3.75	--	4.45	4.29	--	-45(-43)	-20(-29)	--
K	3.64	3.64	--	3.88	4.22	--	-51(-46)	-27(-33)	--
L1	3.67	3.71	--	4.12	4.09	--	-47(-44)	-35(-37)	--
L2	3.69	3.66	--	3.99	3.88	--	-29(-34)	-26(-32)	--

*Temperature at which stiffness of asphalt at 10,000 sec. loading time is equal to 20,000 psi - from Nomograph for Determining Stiffness Modulus of Bitumens (53).

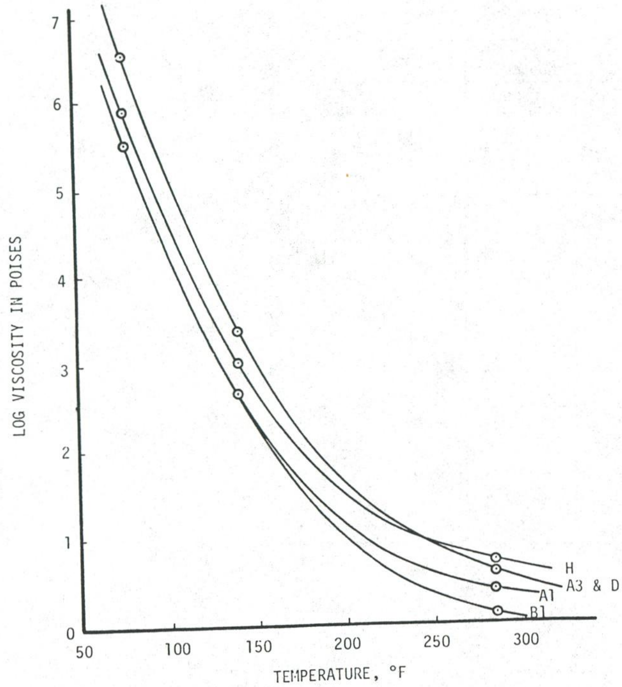


Figure 8. Viscosity as a function of temperature.

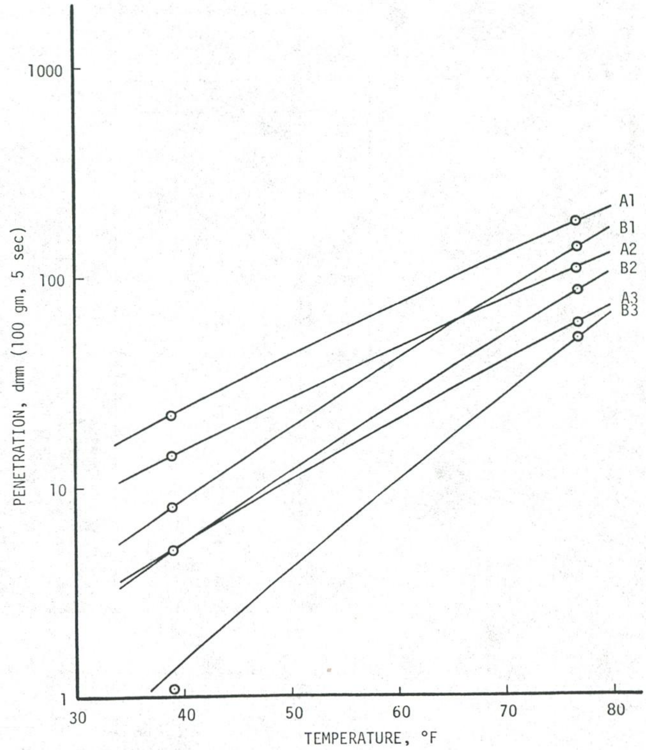


Figure 9. Penetration as a function of temperature.

from this study (dashed lines) is located at lower values of PVN and VTS than the one constructed by Puzinauskas (*54*). A wide variation in temperature susceptibility of the 16 new asphalts is also shown, and was one basis for their selection.

Figure 11 relates PVN and VTS over a range of temperatures from 77 to 140 F (25 to 60 C) for the 16 asphalt cements. Somewhat poorer correlation is indicated here than in Figure 10.

Figure 12 shows only limited correlation between penetration index (Eq. 2, App. D) and PVN (77 to 275 F) (25 to 135 C). The range of temperatures represented by these two parameters is quite different and is a possible reason for the poor correlation.

Figure 13 shows the relationship between two different parameters, both of which are called Penetration Index and are computed by using similar methods (Eqs. 1 and 2, App. D). The method of calculating these two parameters differs in the temperature scale used in the computation (F or C). Equation 1 considers asphalt properties above 77 F; whereas, Eq. 2 considers asphalt properties below 77 F. As a result, the correlation between the two is rather poor.

Effect of Heating on Temperature Susceptibility

Although oven aging will definitely affect the temperature susceptibility of most asphalts, there is no consistency in these effects. Temperature susceptibility of some asphalts increases on oven aging while that of others may decrease and still others exhibit no appreciable change. TFOT and RTFOT induce almost identical changes in temperature susceptibility of individual asphalts (Table 12). Therefore, consistency measurements after RTFOT are not included in Figures 14 through 17.

Figure 14 compares the effects of oven aging on VTS of the 16 asphalts with several asphalts of various grades tested by Puzinauskas (*54*). The diagonal line on this graph indicates equal VTS before and after oven aging. The largest cluster of data points is just above this line, which indicates that most asphalts would be expected to increase slightly in temperature susceptibility in the high temperature range after oven aging. Asphalts C, J, and K will have a lower temperature susceptibility after oven aging.

Figure 15 shows there is remarkably little change in PVN after TFOT (77–275 F) for most of the 16 asphalts tested. PVN (77–275 F) covers a wide range of temperatures, and this could be at least part of the reason for the small changes in temperature susceptibility.

Figure 16 relates PVN (77–140 F) before and after TFOT. This figure indicates that the bad get worse and the good get better. That is, those asphalts exhibiting high temperature susceptibility (low PVN) become more temperature susceptible after TFOT and vice versa.

Figure 17 compares penetration ratio before and after TFOT. Trends similar to those in Figure 16 are exhibited. Penetration ratio appears to be very sensitive to oven aging.

Low-Temperature Asphalt Properties

The research project statement prepared by the NCHRP project panel directed data gathering on the variability in temperature susceptibility of asphalt cements over the full range of construction and service temperatures. Therefore, asphalt cement consistency tests were conducted not only at high temperatures, as discussed previously, but also at low temperatures.

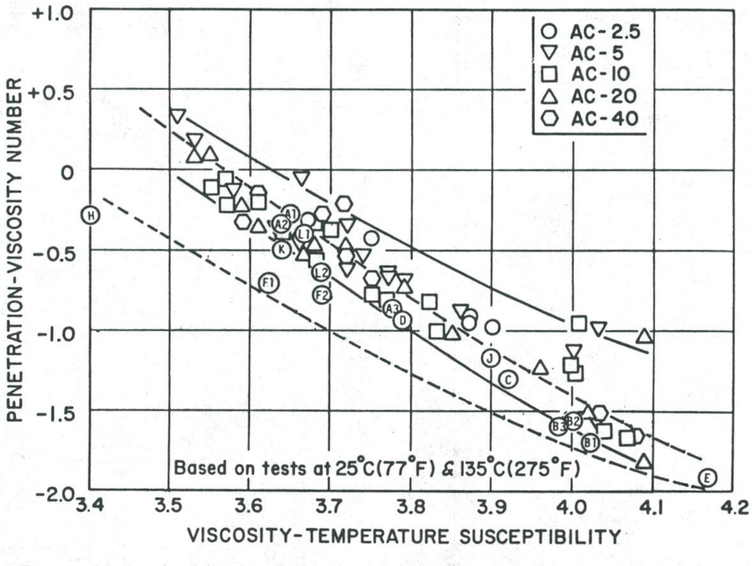


Figure 10. Relationship between viscosity-temperature susceptibility and PVN for asphalt cements. (After Puzinauskas, **54***)*

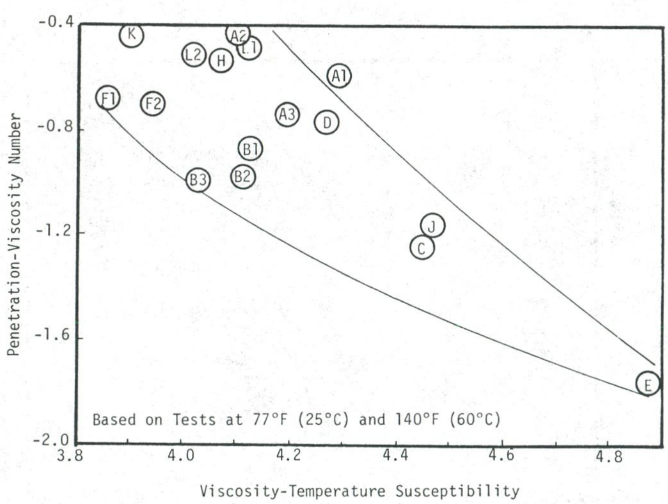


Figure 11. Relationship between PVN and VTS of asphalt cements for a temperature range from 77 to 140 F.

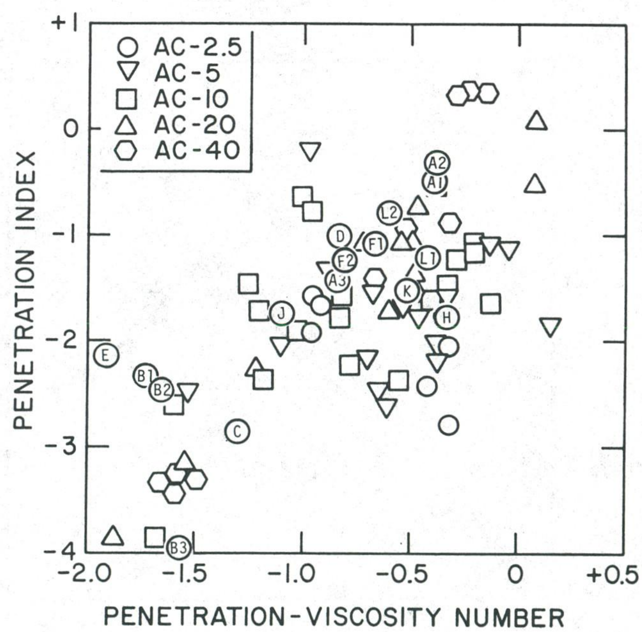


Figure 12. Relationship between PI and PVN for asphalt cements. (After Puzinauskas, **54***)*

The Schweyer rheometer and the Rheometrics mechanical spectrometer were used to obtain the low temperature data on selected original and aged asphalt cements. The asphalt cements were selected to have widely differing temperature susceptibilities.

Viscosity data from the capillary tube viscometer, sliding plate microviscometer, Schweyer rheometer, and the Rheometrics spectrometer have been plotted for 11 of the materials on ASTM D2493 viscosity-temperature charts for asphalts and are presented in Tables E1 through E11, Appendix E.

Viscosities at 77 F (25 C) measured by the sliding plate viscometer are uniformly higher than those measured by the Schweyer rheometer. This was a result of the different shear rates and specimen configurations employed.

Viscosities at 32 F (0 C) measured by the Schweyer rheometer correlate fairly well with those of the Rheometrics device.

All plots (Figs. E1 and E11) appear to approach a viscosity of 10^9 poises as an upper limit. The highly temperature susceptible asphalts (C and E) approach this viscosity at comparatively higher temperatures and exhibit noticeably sharper bends in the curves at approximately 32 F (0 C) (Figs. E4, E5, and E6). They also exhibit larger values of shear susceptibility (Table E1) and have been associated with tender pavements. Asphalt J, which

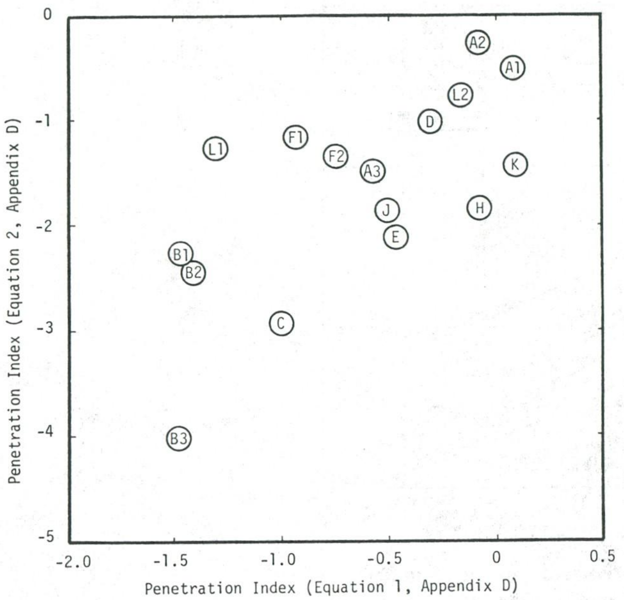


Figure 13. Relationship between PI computed using Eq. 1 and PI computed using Eq. 2, Appendix D.

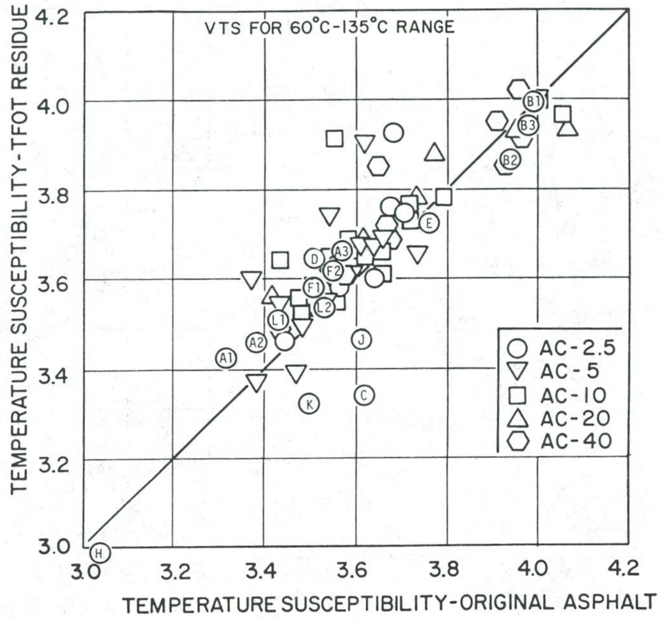


Figure 14. Effect of TFOT heating on viscosity-temperature susceptibility (VTS) of asphalt cements. (After Puzinauskas, **54***)*

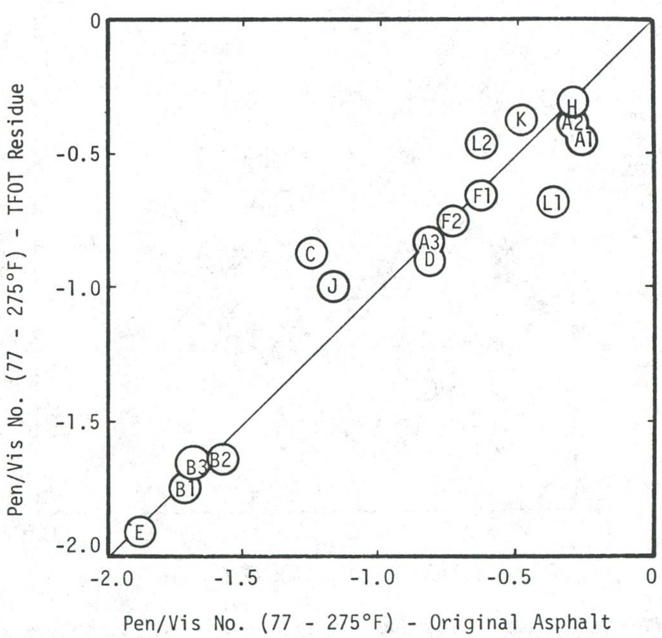


Figure 15. Effect of TFOT on penetration-viscosity number of asphalt cements.

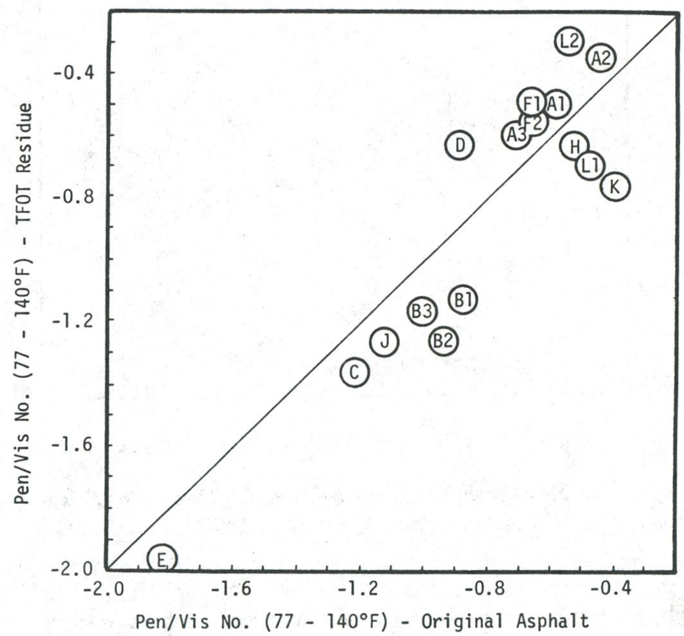


Figure 16. Effect of TFOT on penetration-viscosity number (77-140 F) of asphalt cements.

has been associated with tender pavements, also exhibits a relatively high shear susceptibility (Table E1). This observed relationship between shear susceptibility and pavement tenderness needs additional study.

Several techniques can be used to predict the temperatures at which thermal cracking is likely to occur in the pavements. Penetration, Ring and Ball Softening Point, and other types of asphalt cement consistency data may be used as well as the measurement of asphaltic concrete strengths. Asphalt consistency data were used to determine the temperature at which the stiffness of asphalt cements at 10,000-sec loading time is equal to 20,000 psi (*61*) (Table 12). In general, and as expected, those asphalts with a high temperature susceptibility exhibit a relatively high temperature at which thermal cracking could occur;

in other words, pavements made with these asphalts are more likely to experience thermal cracking.

Table 13 was prepared to illustrate the temperatures at which certain viscosities are obtained. If limiting viscosities could be established, the listed temperatures for given viscosities could be compared with climatic information for a given pavement site to aid in selection of proper grade of asphalt cement.

Asphalt Penetration Versus Time

Standard penetration tests at 77 F were conducted in accordance with a predetermined schedule to determine whether or not "structuring" or "setting" of the asphalt could be detected. The undisturbed asphalt cements were conditioned at 77 F (25 C) for 275 days while covered to prevent surface oxidation. Thirteen asphalts with a wide range of properties were tested, including three that were used in selected field projects (Table 14). Penetration continually decreased (on the average) during the 275-daytime period. At the end of the aging period, the asphalts were heated to 275 F and stirred to eliminate any structuring that may have occurred. Generally, all of the asphalts returned to their original penetration after heating. Figure 18 is a plot of percent decrease in penetration after 103 days versus the asphalt tenderness rating. No correlation is apparent. It is therefore concluded that asphalts will "set up" at varying rates and that this "setting" of asphalts (thixotropic properties) is detectable by using the standard penetration device at 77 F. This structuring can be eliminated by heating the asphalt to about 275 F. Furhter, this structuring does not correlate well with the asphalts' setting rate in the field.

Figure 19 shows penetration as a function of time from 0 to 275 days for the original and thin-film oven-aged asphalts from field projects (described in the next section of this report) located at White Deer, Texas, and Glendive, Montana. The original White Deer asphalt is harder at 77 F (lower penetration) than the original Montana asphalt; but the order is reversed on the asphalts tested after TFOT. The Montana asphalt is significantly more susceptible to oven aging than the White Deer asphalt. Near 100 days of conditioning, the two oven-aged asphalts approach the same value of penetration (Fig. 19). The White Deer paving mixture was slightly tender during construction and slow setting after construction. The Montana paving mixture was tender during construction (difficult to compact at conventional temperatures with conventional equipment), but it was quite tough as soon as the pavement cooled to ambient temperature. Resistance to hardening during mixing exhibited by the White Deer asphalt appears to be related to the tenderness exhibited during the early life of the pavement. After the White Deer mixture "set up," it became fairly tough as evidenced by only slight rutting after a very hot summer and heavy traffic loads. (Note: The White Deer asphalt was produced by Refinery 4-9.)

Asphalt Viscosity Versus Time

Four asphalt cements were selected, and the viscosity at 77 F was measured as a function of time (Table 15). A sliding glass plate microviscometer was used to measure viscosity. Test specimens were prepared in the usual fashion between two glass plates and stored undisturbed at 77 F in the absence of direct light for predetermined periods of time prior to measuring viscosity. Figure 20 shows consistent increases in viscosity with time as well as fairly large variation in the viscosity measurements. Since the asphalt specimens were shielded from light and the bulk of the specimens protected from oxidation, it is assumed that the increases in viscosity are related to thixotropic properties of the asphalt cements. "Structuring" rates of the different asphalts (slope of the curves) vary significantly.

Asphalt C is highly temperature susceptible and reputed to produce tender and slow setting mixtures. Asphalt C exhibited the lowest initial viscosity at 77 F and a relatively slow setting rate when compared to the other asphalts tested. It appears that the problems associated with this asphalt are most likely due to the low initial viscosity as well as the slow-setting rate.

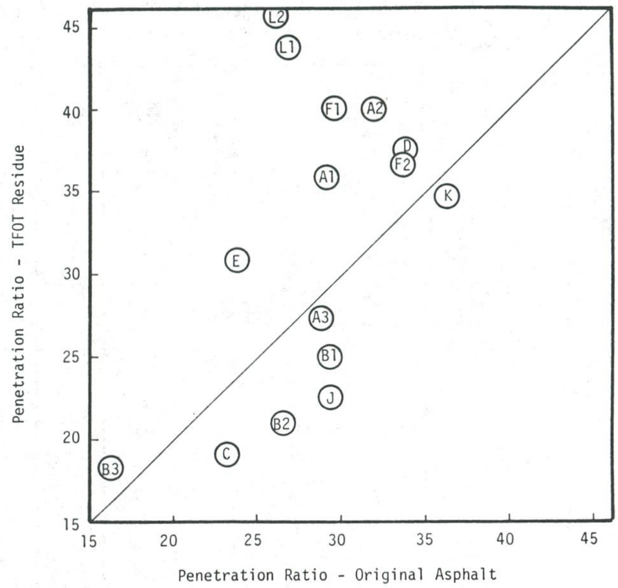


Figure 17. Effect of TFOT on penetration ratio of asphalt cements.

Table 13. Low-temperature viscosity of selected asphalts.

Asphalt Code	Condition	Temperature at which viscosity is given value, °F			
		1 x 10^5 Poises	1 x 10^6 Poises	1 x 10^7 Poises	1 x 10^8 Poises
A2	Original	87	65	41	10
	TFOT	95	71	50	20
	RTFOT	95	71	48	13
C	Original	87	69	54	38
	TFOT	93	72	57	39
E	Original	98	80	64	39
F1	Original	89	68	48	24
	TFOT	102	77	53	25
	RTFOT	100	73	50	21

Table 14. Penetration at 77 F as a function of time for asphalt-cements aged at 77 F. Each value is an average of 3 tests.

Asphalt Identification	Penetration at given number of days										
	0	2	3	14	28	53	103	160	220	275	275*
A2 (AC-10)	89	85	85	78	82	78	74	60	55	56	77
B1 (AR 1000)	126	128	132	125	130	115	135	118	120	---	135
B2 (AR 2000)	86	84	85	84	103	87	78	72	72	57	85
B3 (AR 4000)	50	51	48	49	55	49	41	30	24	32	47
C (120-150)	105	101	103	104	101	85	90	81	80	70	112
J (85-100)	91	91	93	82	60	72	71	72	55	55	80
K (AR 2000)	193	190	198	192	195	165	172	170	168	131	183
L2 (AC-20)	72	70	62	63	60	57	64	55	45	46	61
Warren-Scapoose, Oregon	44	44	43	47	46	43	37	31	25	24	43
WD Original	103	100	98	93	90	80	76	70	65	56	98
WD after TFOT	69	70	59	57	57	50	51	48	40	41	61
GM Original	113	113	111	104	100	102	91	86	70	66	105
GM after TFOT	56	58	55	54	54	52	48	49	39	39	59

*Penetration at 77° F after reheating to 275° F and stirring to eliminate thixotropy.

Table 15. Viscosity vs time for asphalt cements aged at 77 F.

Aging Time, days	Viscosity @ 77° F, poise x 10^5			
	B2(AR2000)	C(120-150)	H(AC-10)	(AC-10)
0	9.5	4.6	19	19
0.25	----	5.3	--	17
1	11.0	7.8	15	31
2	8.5	6.2	--	11
5	10.0	6.0	--	20
7	11.0	9.8	--	40
14	9.5	8.1	24	23
21	11.0	8.8	--	--
28	9.5	9.0	23	40
60	----	6.8	35	67
75	----	---	--	--
125	----	12.5	--	42
150	----	---	36	50
225	----	13.5	--	--

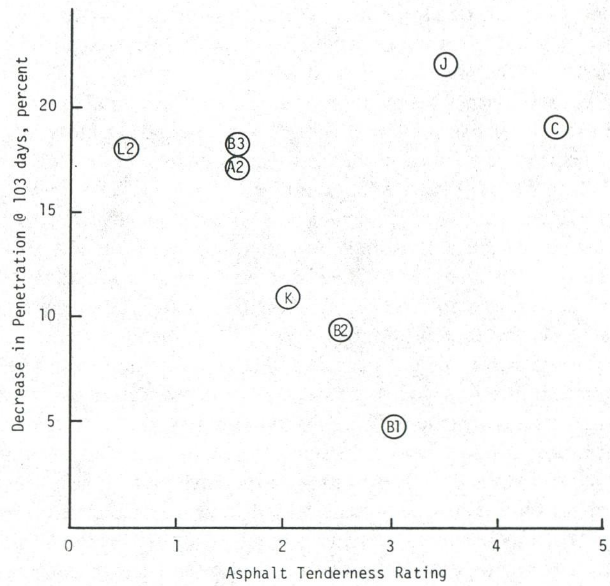


Figure 18. Decrease in penetration versus asphalt tenderness rating.

Asphalt H is not highly temperature susceptible but has been associated with slow-setting pavements. Asphalt H and the White Deer asphalt were produced at the same refinery. Both the viscosity as a function of time (Fig. 20) and the penetration as a function of time (Table 14) show that the consistency of Asphalt H (or the White Deer asphalt) increases faster than that of Asphalt C. On the basis of comments by users of these asphalts, this difference is reflected by their setting rates in the field.

Asphalt B2 and the asphalt from Refinery 4-1 are both highly temperature susceptible. However, the asphalt from Refinery 4-1 exhibits a comparatively rapid increase in viscosity with time; whereas, Asphalt B2 exhibits almost no increase in viscosity with time. This correlates reasonably well with user comments about these asphalts.

Viscosities of Asphalts C and 4-1 were measured after reheating. However, they were not heated to 275 F. They were heated using the heating lamp that is employed during prepa-

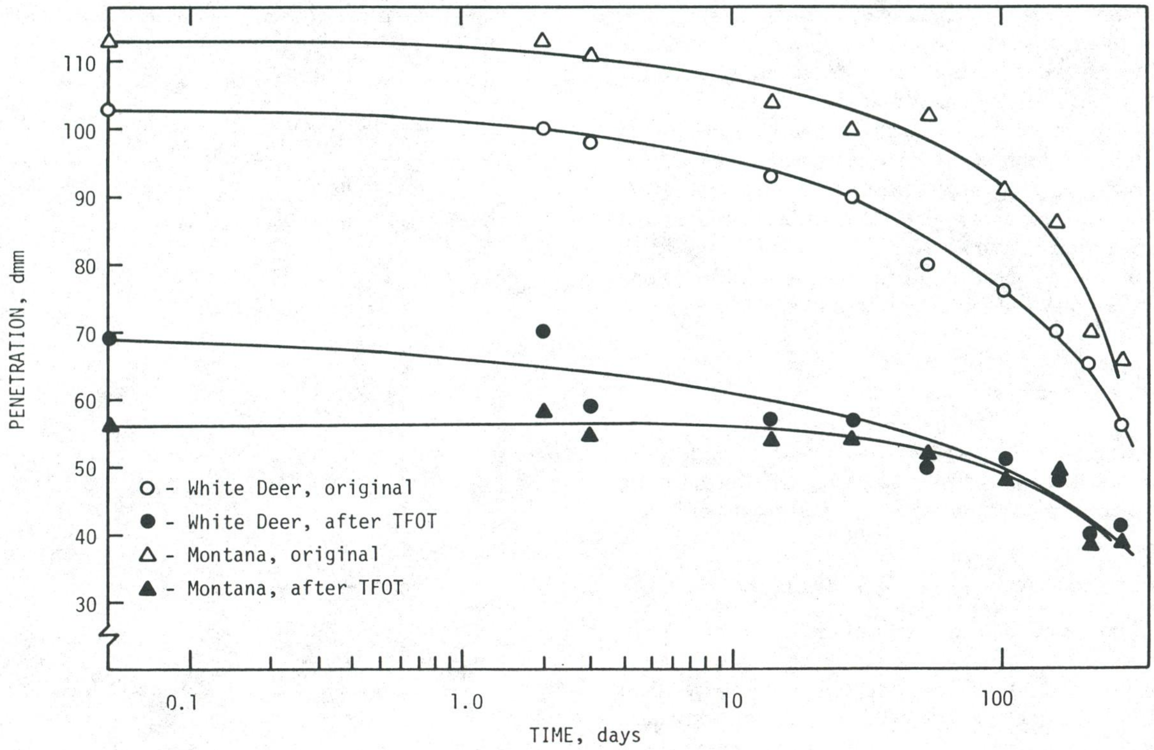


Figure 19. Penetration at 77 F as a function of time for asphalts aged at 77 F.

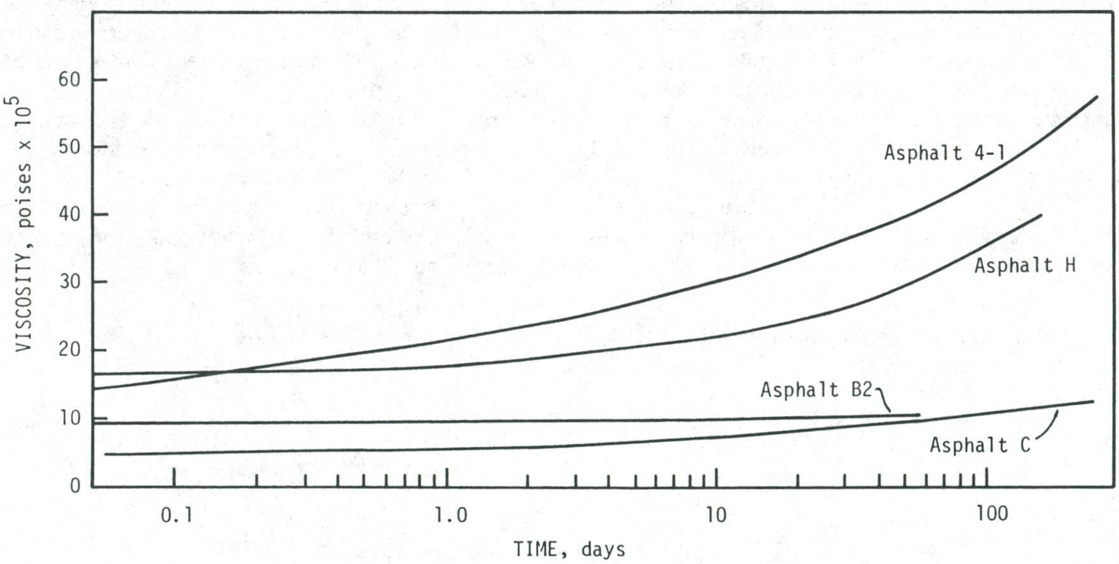


Figure 20. Viscosity at 77 F versus time for asphalts aged at 77 F.

ration of the asphalt test specimens used with the microviscometer. Most likely a temperature of only 160 to 180 F was attained. The viscosity of Asphalt 4-1 returned to its original value, while the viscosity of Asphalt C remained at the aged value.

This short experiment was performed primarily to determine whether or not the sliding plate microviscometer is capable of detecting structuring or setting of asphalt cement. Apparently, it is. Furthermore, these data indicate that setting rate of asphalt is not related to temperature susceptibility. In order to define criteria which can be applied to predict the probability of slow-setting mixtures, much more testing would be required.

Rostler-Sternberg Analysis

Chemical analyses of the seven asphalts used in the mixture study (discussed later) plus two others were determined using the Rostler-Sternberg procedure (*14, 33*). Test results are given in Table 16.

The Rostler parameter, $\frac{N + A_1}{P + A_2}$, is a ratio of the concentration of the more reactive components to the less reactive components. Rostler (*15*) claims this is an expression relating composition to durability. For example, a value of less than 1.14 is said to be characteristic of excellent abrasion resistance. Table 17 lists the characteristics of the asphalt components identified by this test.

Asphalts C and H are shown to contain very low percentages of asphaltenes. This indicates that the systems are well solvated; that is, the asphaltenes are highly peptized. Both of these asphalts are reputed to produce slow-setting mixtures. Hveem et al. (*3*) pointed out that in their field observations, "asphalts which produced slow setting mixtures were very highly peptized sols that displayed almost pure Newtonian behavior and that, as expected, they were also quite temperature susceptible." However, in this instance, Asphalt H is not highly temperature susceptible. Nevertheless, it appears that mixture tenderness or possibly setting rate may be related to asphaltene content of the asphalt (Fig. 21). The most troublesome asphalts (C, J, H, and B1) are those that are low in asphaltenes and have high penetrations at 77 F. Asphalt H exhibited inexplicable anomalies during repeated trials of the Rostler-Sternberg analysis; therefore, satisfactory results were not obtained.

Table 17. Characteristics of asphalt components from Rostler-Sternberg chemical analysis.

Fraction	General Description	Specific Chemical Reactivity	Significant Function
A Asphaltenes	Higher molecular weight condensation products	Insoluble in n-pentane	Bodying agent
N Nitrogen Bases	Petroleum resins containing nitrogen bases and other highly reactive compounds	Precipitable with 85% H_2SO_4	Peptizer for asphaltenes
A_1 First Acidaffins	Resinous hydrocarbons	Precipitable with concentrated H_2SO_4	Solvent for peptized asphaltenes
A_2 Second Acidaffins	Slightly unsaturated hydrocarbons	Precipitable with fuming H_2SO_4 (30% SO_3)	Solvent for peptized asphaltenes
P Paraffins	Saturated hydrocarbons	Non-reactive with fuming H_2SO_4 (30% SO_3)	Gelling agent

After Reference 14

Asphaltene content and temperature susceptibility for 70 asphalts were tabulated by Anderson and Dukatz (*55*). These data are plotted in Figures 22, 23, and 24 along with the data generated in this research study. The figures clearly show there is no correlation between asphaltene content and asphalt temperature susceptibility.

Rostler analyses of the asphalts used in the ongoing field projects (Table B1) also indicate that the slower setting materials (WD and AO) are low in asphaltenes.

Figure 25 shows that there is no correlation between structuring rate of asphalts, as measured by the penetration versus time test, and asphaltene content.

Table 16. Results from Rostler-Sternberg chemical analyses of asphalts used in mixture study.

Sample I.D.	Asphaltenes A (percent)	Nitrogen Bases N (percent)	1st Acidaffins A_1 (percent)	2nd Acidaffins A_2 (percent)	Parafins P (percent)	$\frac{N + A_1}{P + A_2}$	$\frac{N}{P}$
A2	23	17	20	28	12	0.96	1.49
B1	9	35	17	21	18	1.31	1.91
B2	9	35	18	19	19	1.43	1.87
B3	8	45	13	19	16	1.70	2.88
C	5	27	21	24	23	1.02	1.20
H	5	--	--	--	20	----	----
J	14	25	19	22	20	1.06	1.27
K	24	30	16	14	16	1.54	1.89
L1	20	13	16	22	30	0.55	0.43

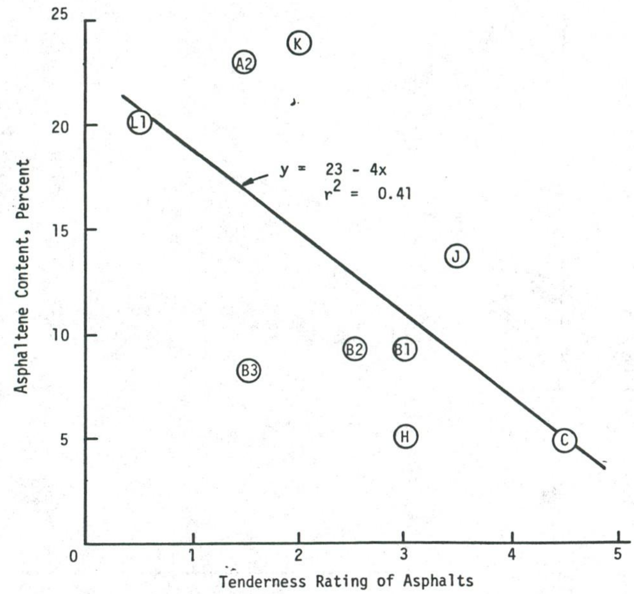


Figure 21. Asphaltene content versus asphalt tenderness rating.

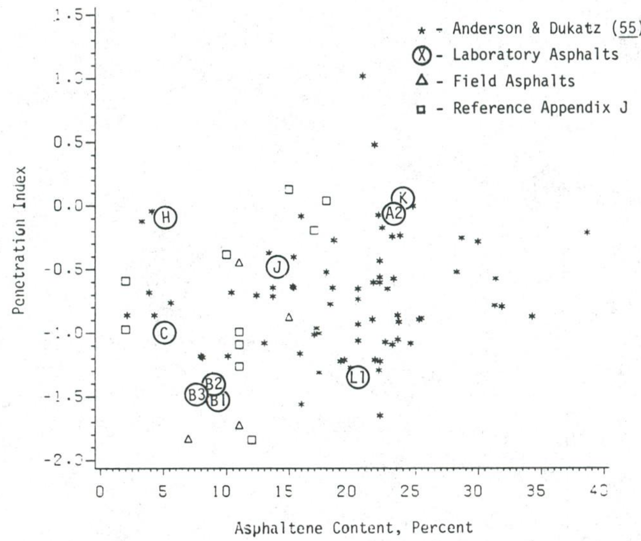


Figure 22. Penetration index (Pfieffer & Van Doormal) as a function of asphaltene content (pentane precipitate) of original asphalts.

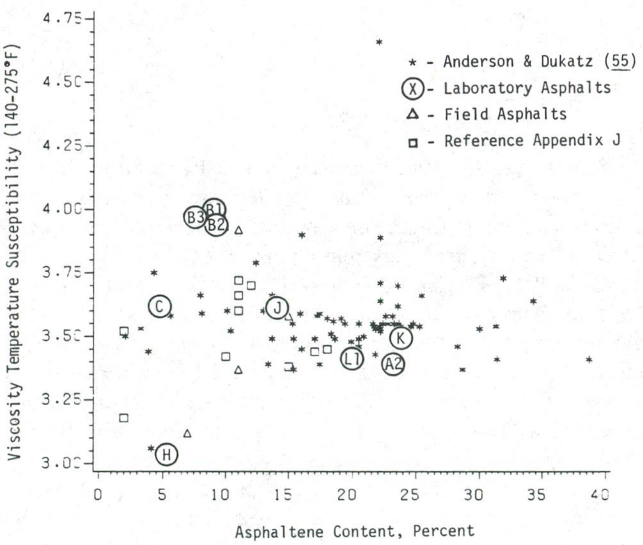


Figure 23. Viscosity temperature susceptibility as a function of asphaltene content (pentane precipitate) of original asphalts.

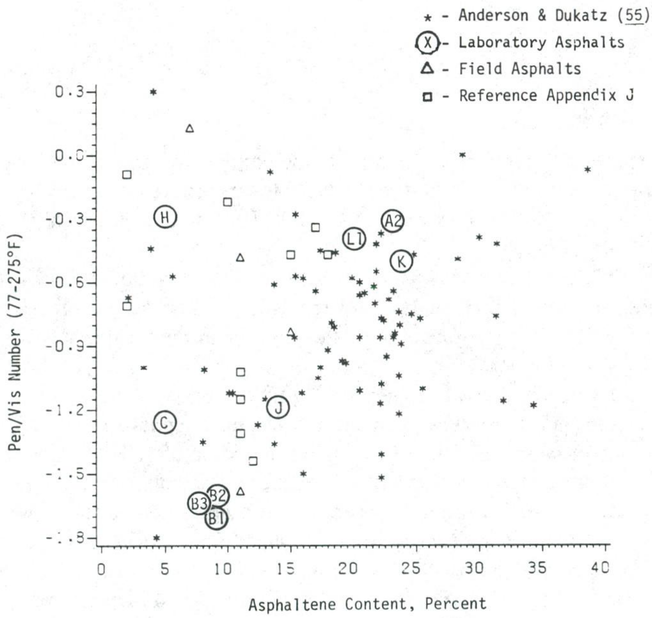


Figure 24. Pen/vis number as a function of asphaltene content (pentane precipitate) of original asphalts.

Asphaltene Settling Rate Tests

Plancher (*62*) indicated that asphaltene settling test data might be useful in identifying those asphalts most likely to produce tender mixes. He postulates that "tender" asphalts would be expected to exhibit large increases in settling time in conjunction with a comparatively small increase in viscosity after the rolling thin film oven test (RTFOT). He further indicates that greater asphaltene dispersion will be evidenced by longer settling times (i.e., the more highly peptized asphaltenes will exhibit longer settling times.

Asphaltene settling tests were conducted on seven asphalts with widely varying properties of temperature susceptibility and relative tenderness. Results are presented in Table 18. Asphalts B1, B2, and B3 were produced at the same refinery and normally behave similarly. Asphalts B1, B2, and B3 are only occasionally reported to produce tender or slow-setting paving mixtures.

Asphalts C and J are highly temperature susceptible and

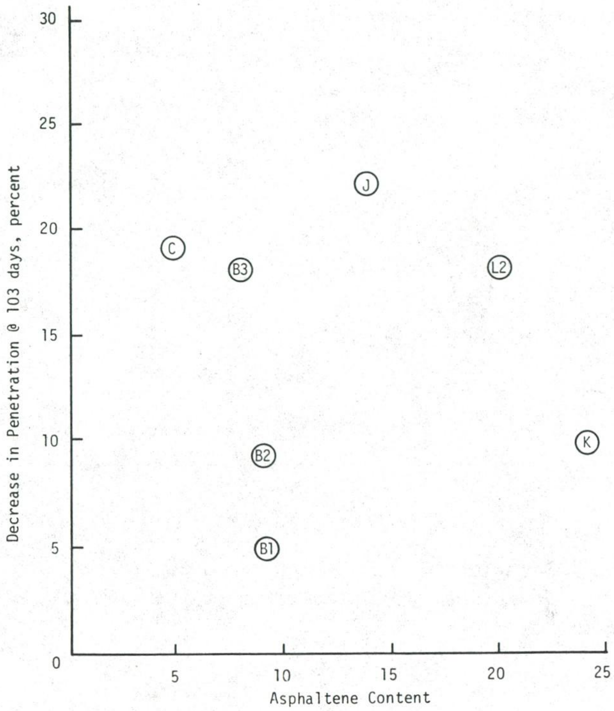


Figure 25. Decrease in penetration after 103 days at 77 F versus asphaltene content.

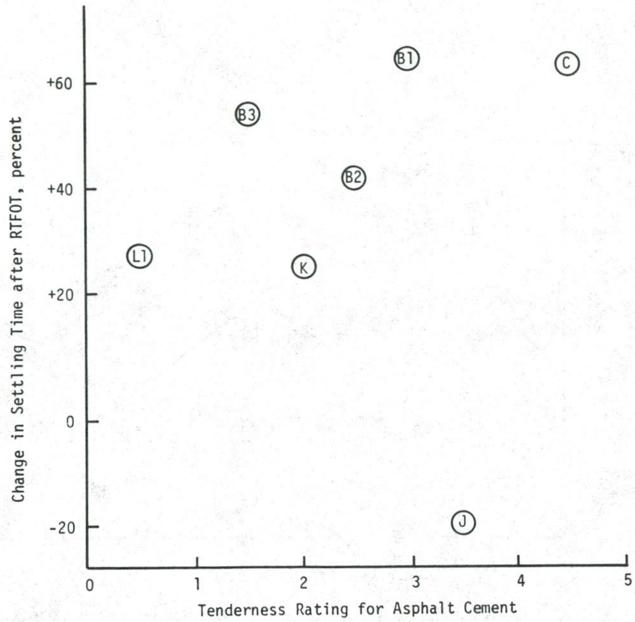


Figure 26. Change in settling time before-and-after RTFOT versus tenderness rating for asphalt cements.

reputed to frequently produce tender and slow-setting paving mixtures. Asphalt C showed a relatively large increase in settling time after RTFOT; whereas Asphalt J showed a decrease in settling time.

No asphaltene settling was observed for Asphalt H. This asphalt also defied analysis by the Rostler-Sternberg method. Asphalt H has previously been shown to be an unusual material (Figs. 2 and 10).

Asphalts K and L1 are neither highly temperature susceptible nor reputed to produce problem mixes. These asphalts exhibited comparatively small increases in settling time after RTFOT.

Unfortunately, the asphaltene settling test results do not correlate well with asphalt temperature susceptibility or the likelihood of the asphalt to produce tender or slow-setting mixtures (Fig. 26). On the basis of this asphaltene settling study of admittedly limited scope, this method is not recommended as a method to identify problem asphalts. Additional study may reveal reliable correlations.

Gel Permeation Chromatography

Liquid chromatography has been shown to be an important analytical tool for characterizing properties of crudes and their refined products (*63*). Gel permeation chromatography (GPC) is used to show the distribution of molecular size of the different chemical components within an asphalt. This test was conducted to provide a comparative visual representation of the chemical constituents of several of the asphalts investigated in this study. GPC chromatograms are presented in Appendix I.

Asphalt samples were dissolved in tetrahydrofuran (THF), which was used as the mobile liquid phase or carrier. GPC separations were performed on a Waters Associate Model ALC/GPC 202 liquid chromatograph equipped with a refractometer (Model R401). The instrument was operated at ambient temperature. Approximately 40 microliters of each sample were injected into the gel columns under a solvent flow rate of 1 milliliter per minute. GPC separations are based primarily on the size of the molecule rather than molecular weight. Larger molecules will elute faster than smaller molecules because the smaller molecules become temporarily trapped inside the pores of the gel. The chromatograms are based on the difference between the refractive index of the asphalt molecules and the tetrahydrofuran. One must bear in mind that data obtained by GPC do not represent actual, absolute, molecular weight values of asphalt compounds because the system has been calibrated using polystyrene standards. Besides, it is known that factors such as the adsorption of polar compounds on the gel and/or intermolecular associations of polar compounds can affect GPC results (*64, 65*). Each factor affects the results in a different way. Adsorption on the gel would result in lower apparent molecular size values, while the association of these compounds would cause earlier elution, giving apparent molecular size values higher than the actual values.

Chromatograms for the field asphalts are shown in Figures 11, 12, 13, and 14, Appendix I. The asphalt from the White Deer, Texas, field project (Fig. 12) appears to be most unusual. It is shown to contain a greater concentration of molecules in the large molecular size (LMS) region. Chromatograms of the remaining field asphalts (Figs. 12 through 14) are comparable

Table 18. Results from asphaltene settling rate tests before-and-after rolling thin film oven test.

Sample I. D.	Settling Time, Minutes*						Change in Settling Time after RTFOT, percent	Viscosity Ratio @ 140°F after RTFOT
	Original Asphalt			After RTFOT aging				
	Run #1	Run #2	Average	Run #1	Run #2	Average		
B1 (AR 1000)	17.0	19.6	18.3	29.0	31.5	30.0	+64	1.74
B2 (AR 2000)	28.7	24.0	26.4	38.5	35.5	37.5	+42	1.64
B3 (AR 4000)	18.4	21.2	19.8	32.0	29.0	30.5	+54	1.71
C (120-150)	19.2	17.5	18.4	28.0	32.0	30.0	+63	1.92***
H (AC-10)	**	**	**	-	-	-	-	
J (85-100)	37.2	35.0	36.1	30.0	28.0	29.0	-20	2.04***
K (AR 2000)	10.0	7.0	8.5	10.0	11.0	10.5	+24	1.91***
L1 (AC-10)	46.2	45.5	45.9	57.0	62.0	59.5	+27	1.81***

*The time it takes the asphaltenes to reach the 25-ml level in the graduated cylinder is defined as the asphaltene settling time and measures the degree of peptization of asphaltenes in the maltenehexane solution (Plancer, et. al., "A Settling Test to Evaluate the Relative Degree of Peptization of Asphaltente's, Laramie Energy Technology Center, D.O.E.)

**Repeated tests showed no settling of asphaltenes for Asphalt H.

***After TFOT.

to most of the other asphalts tested in this study and to "typical" asphalts found in the literature (*63, 64*).

Chromatograms for the asphalts used in the laboratory test program are shown in Figures I5 through I11. Asphalts C and H, which are reputed to be slow setting, exhibit tall, slender chromatograms. However, Asphalt H is shown to have the higher concentration of large molecules. (Note that Asphalt H and the asphalt used in the White Deer paving mixture were both produced at Refinery 4-9.) Although Asphalt H is shown to have a comparatively high concentration of large molecules, it is shown by the Rostler-Sternberg analysis to contain a comparatively low percentage of asphaltenes and, furthermore, when subjected to the asphaltene settling test, no asphaltenes were precipitated by the hexane solvent. Asphalt C is also comparatively low in asphaltenes.

Asphalt K (Fig. I10) shows a rather unusual chromatogram. It has a tall peak in the LMS region and is "bumpy" in the medium molecular size (MMS) region. The tall peak suggests a high concentration of asphaltenes, which is confirmed by the Rostler-Sternberg analysis. The bumpy region suggests that Asphalt K is a blend of two or more materials. This material is refined from a very heavy crude that is recovered by pumping liquid fuel oil into the ground to soften it. Then it is pumped out and refined in the conventional manner.

The family of chromatograms for Asphalts B1, B2, and B3 indicate a slight movement toward the LMS region as the paving grade (AR-1000, AR-2000, and AR-4000, respectively) approaches a higher viscosity. This is as it should be.

Chromatograms of AC-10 asphalt cements representative of those used at the Dickens and Dumas, Texas, field tests are shown in Figures I12 through I16. The asphalt from Refinery 4-9 (Fig. I13) appears to be an unusual material. The reader is reminded that Asphalt H and the White Deer asphalt were produced in Refinery 4-9. Notice that the chromatograms in Figures I2, I9, and I13 are similar in shape. The asphalt from Refinery 4-5 (Fig. I16) exhibits a sharp peak in the LMS region. Although the asphalts used in Dickens and Dumas, Texas, vary widely in chemical and physical properties, there were no distinguishable differences in the workability of paving mixtures during construction.

FIELD-LABORATORY TEST PROGRAM

The intent of this phase of the research program was to investigate in detail a minimum of 10 construction projects in which asphaltic concrete placement difficulties were encountered, and 6 projects in which placement difficulties were not encountered. A review of tender mixture problems and conclusions from some recent surveys of asphalt users will be presented prior to the results from the testing program.

Definitions and Causes of Tender Mixtures

Tender or slow-setting asphalt pavements have been defined by The Asphalt Institute as mixtures which have very low resistance to deformation by "punching loads" and/or scuffs under horizontally applied shearing loads after compaction has been completed (*66*). In general, tender mixes are difficult to roll, difficult to achieve specified density, and occasionally rut; they will also displace under high pressure and shove and scuff under traffic. However, some tender mixtures compact with little difficulty, but remain soft and scuff under traffic.

The causes of tender mixes have been defined by a number of investigators. Among the most recent work is that performed by the Chicago Testing Laboratories, Inc. (*67*), Texas A&M University (*68*), and Santucci and Schmidt (*69*). The authors of these papers as well as others suggest that the following factors are related to tenderness or slow-setting asphalt mixtures:

1. Asphalt temperature susceptibility (*39, 70, 71, 72, 73*).
2. Asphalt viscosity (*39, 71, 72, 73, 74, 75*).

3. Asphalt composition-crude source and refining method (*76, 72, 77, 78*).

4. Durable asphalts highly resistant to hardening (*78*).

5. Asphalt cement setting properties (*69, 78, 79*).

6. Aggregate gradation-low % fines (−200) and high % sands (*72, 73, 77, 79*).

7. Aggregate angularity and surface texture (*39, 72, 73, 79*).

8. Selective absorption of asphalt components by active aggregate surfaces (*3*).

9. Compactive effort—overstressing mixture (*77, 79*).

10. Size, shape, and amount of fines (−200) from air quality equipment (*68*).

11. Moisture content of mixture (*79*).

From this listing it is evident that both the aggregate (gradation, top size, particle shape, and particle surface characteristics) and bituminous binder (viscosity, temperature susceptibility, chemical composition make-up) contribute to tenderness. However, it is a general belief that changes in the aggregate mixture are more effective in reducing or eliminating tenderness than changes in the consistency of the binder.

A paper by Schmidt et al. (*80*) illustrates the importance of the rheology of the asphalt plus filler to cohesion (measure of tenderness) during rolling. By extrapolating data from Nijboer (*81*), the author indicates that a tenfold increase in cohesion will occur when varying the filler content from 2 to 5 percent. Similarly, the cohesion of a mixture can decrease by a factor of two if the filler particle size is reduced from 100 to 10 microns. For comparison purposes, it can be shown that less than a twofold increase in cohesion can occur if the asphalt is changed from a 200-300 penetration grade to a 40-50 penetration grade. The work by Schmidt et al. (*80*) also illustrates the importance of the reintroduction of fines collected in bag houses and other types of collection equipment on the properties of the paving mixture; careful control is advised. Additionally, Gietz (*82*) showed that temperature susceptibility of asphalt/filler mixtures can change significantly on heating in the RTFOT, depending on the effects of the mineral filler on the asphalt.

The presence of wax in asphalts is believed to contribute to tenderness problems. However, The Asphalt Institute (*66*) states that there is no factual documentation to support this claim. In a rather extensive research program with waxy asphalts, DeBats (*83*) does not mention any tenderness problems; in fact, he declares no harmful effects were evident from the presence of wax. However, Gallaway and Epps (*68*) reported to NAPA that 5 percent wax added to an asphalt created a significant drop in resilient modulus of laboratory samples at critical temperatures between 100 and 140 F (near the melting point of wax).

During the course of this research, it has become apparent that there are two distinctly different types of paving mixtures that are commonly referred to as "tender." One exhibits tenderness *during* construction, which is characterized by being easily overstressed during compaction, that is, shoving under steel wheel rollers or resisting compaction at normal temperatures. The other mixture is slow setting *after* construction, which is characterized by plastic deformation or scuffing within a few weeks after construction, particularly during periods of hot weather. Mixtures frequently exhibit both of these characteristics.

In the past, many researchers have combined these two mixtures under one category and conducted tests in an attempt to relate "tenderness" to some particular asphalt cement or paving mixture property. It appears that asphalts from the two types of mixtures described above should be treated separately.

Tenderness during construction is primarily an aggregate problem (caused by smooth, rounded aggregate, a high percentage of sand-size particles and/or a low percentage of filler size particles) which is aggravated by a highly temperature susceptible asphalt. This mixture must be allowed to cool until the asphalt viscosity increases to a point where sufficient internal friction will prohibit overstressing by the steel wheels of the breakdown roller. Tenderness after construction is an asphalt cement related problem (caused by a slow setting asphalt) which will manifest itself only when used with an aggregate composed of a critical gradation. The problem usually disappears after a few weeks when the asphalt "sets up."

Tenderness during construction appears to be related to asphalt temperature susceptibility; whereas tenderness after construction appears to be related to chemical properties of the asphalt cement such as asphaltene content or degree of peptization. A slow-setting mixture will usually show some degree of tenderness during construction, but a mixture that is tender during construction may not be slow setting. A slow-setting mixture is presently more difficult to accommodate than a mixture that is only tender during construction.

Recent Surveys of Asphalt Users

From the foregoing brief discussion, it is apparent that a number of factors contribute to tender mixes. For a particular project experiencing tender mix problems, it is often difficult to define the exact cause of the problem (*68*). However, people involved with construction on the west coast have cited reasons as follows:

1. AR specifications too broad.
2. Reduced mixing temperatures to save fuel (less hardening).
3. Increased use of drum mixing.

Other reasons cited during a survey conducted by the National Asphalt Pavement Association in 1975 include the use of a low viscosity asphalt, excessive fines, asphalts from particular sources, and the nature and amount of filler used. The States of Washington, Oregon, Michigan, Illinois, Oklahoma, Iowa, Minnesota, Indiana, Pennsylvania, New York, and New Jersey have recently reported tender mix problems (*84*).

In a 1977 Survey of Problems and/or Variability in Asphalt Materials conducted by AASHTO (*85*), just over 50 percent of the 50 states replying indicated some problems with asphalt cement. All but four, including one who indicated no problem, thought asphaltic materials were "different" in those 4 years just past the oil embargo. Practically all the replies indicated that the problems and the differences involved materials which met specifications, but possibly in a different area of the specified range of values. The following conclusions were presented by AASHTO (*85*).

1. There is evidence that some asphalt materials supplied are different from those supplied before the energy crisis.

2. The material supplied in practically all cases meets governing specifications.

3. Adoption of new grading systems in some instances oc-

curred shortly before or coincidental with the energy crisis. In addition, lower mixing temperatures keyed to the energy situation and/or drum mix plants were implemented by some agencies.

4. Suppliers were forced, or elected, to use different crude sources during the energy crisis or to conform to new grading specifications.

5. As a result of No. 3 and No. 4 above, some asphalt cements, while still meeting specifications, exhibited different properties within the range of required values. Generally these changes were in a marginal direction and away from midrange values.

6. These different asphalt properties are identifiable and the behavioral consequences are predictable.

7. Corrective changes in design and construction practices to accommodate adverse circumstances take time to understand and implement. In some instances, the consequences might involve acceptance of conditions previously considered less than desirable.

8. An effective training program to reeducate design, construction, and maintenance people to new asphalt properties and behavior will greatly lessen the problems in those agencies where crude supplies have changed and/or where new grading systems for asphalt cement have been adopted.

During the conduct of this NCHRP Project 1-20 research study (fall of 1979), about half the state materials engineers were contacted personally or by phone in the search for historical asphalt data for the variability study. They were also questioned about asphalt variability and performance during construction and early pavement life. Most of those surveyed indicated no abnormal variability in asphalt properties. A few, however, stated that they had seen considerable variability in the temperature susceptibility of asphalts from a single manufacturer, particularly since the beginning of the energy crisis. About half of them claimed to have experienced asphalt-related construction difficulties or instability in newly constructed pavements. The single most severe and most frequently mentioned asphalt problem in this survey was water susceptibility.

Overview of Test Program for Field Mixtures

The objective of this task of the NCHRP Project I-20 study was to establish a relationship between asphalt cement properties and construction problems. If relationships can be established, the engineer will be in a better position to accommodate the variability in asphalt properties and/or establish a rational specification for asphalt based on pavement performance.

In an attempt to locate pavements with tenderness problems, a phone request to state materials engineers was made and requests were published in newsletters of the National Asphalt Pavement Association and The Asphalt Institute. The intent of this effort was to locate construction sites, observe and evaluate the problems, and, if deemed appropriate, obtain samples for testing in the laboratory. Initially, only two responses were received both of which were mixture tenderness problems but were determined to be related to aggregate type and/or gradation and not the asphalt.

Since ongoing construction projects experiencing asphalt-related construction difficulties could not be located for testing according to the original plan, the test plan was modified to include testing of mixtures from "completed" pavements that had experienced asphalt-related problems during construction or stability problems early in the pavement's life, and similar pavements that had acceptable performance during construction and early life.

Later, 7 additional ongoing construction projects were located that were experiencing construction and/or early performance problems which the contractor blamed on the asphalt. Materials were received from Tennessee, California, Illinois, New York, Texas, Montana, and Oklahoma. Preliminary laboratory tests were performed on those materials which indicated four of them were unsuitable for further study either because the problem was obviously due to the aggregate or because the mixture was contaminated.

Materials

Four-inch diameter cores were obtained from 11 different pavements located in 6 different states. In each case, the asphaltic concrete surface (the last overlay) was the layer of interest. One disadvantage was that the thickness of the layers was only about 1.5 in. Thus, core specimens obtained from the pavements were quite thin.

Table 19 gives a brief summary of the pavements tested which includes location, description of materials, and comments on construction and early-life performance. Note that core samples identified as TA, WL, and WW contained Asphalts H, F1, and F2, respectively. These asphalts were characterized in the previous section of this report. Pavements AG, I, and WD contained asphalts from the same producers as Asphalts C, J, and H, respectively, but from a different production period.

A subjective evaluation of the mixtures was made by the research team primarily on the basis of discussions with the highway department personnel supplying the mixtures and asphalts. The mixtures were rated according to tenderness on a scale from 0 to 5; 0 representing no tenderness and 5 representing extreme tenderness. This was done to facilitate comparisons of laboratory-measured asphalt and mixture properties to difficulties experienced in the field. The values assigned to the mixtures are given in Table 19.

Testing of Original Cores and Remolded Cores

Pavement core specimens were subjected to a battery of tests to determine the engineering properties of the mixtures, aggregates, and asphalt cements. The test program shown in Figure C1, Appendix C, was designed specifically to identify tender or slow-setting asphaltic concrete mixtures.

Resilient modulus as a function of temperature was measured to determine the temperature susceptibility of the asphalt-aggregate mixtures.

After determining Hveem and Marshall stabilities and tensile properties of the cored materials, the failed specimens were heated to 250 F (121 C), mixed in a mechanical mixer and remolded into cylindrical specimens 4 in. in diameter and approximately 2 in. in height. Molding was in accordance with test method Tex-206-F, Part II, "Motorized Gyratory-Shear Molding Press Operating Procedure" (*86*). As soon as the remolded specimens reached the appropriate temperature, Mar-

Table 19. Information on cores tested.

Code	Const. Date	Pavement Location	Asphalt Description	Aggregate Description	Remarks of State Personnel	Tenderness Rating
AG	1979	Ganado, Arizona US 63	AR 2000 (From same refinery as Asphalt C) Temperature Susceptible	Crushed rock Field Sand	Very tender during and after construction Some Rutting	4
AT	1979	Texas Canyon, Arizona IH-10	AR 2000 + Antistrip Producer same as AC (below) West Texas Temperature Susceptible	River gravel with 40% crushed faces River sand	Very tender during and after construction Additional-#200 aggregate eliminated construction tenderness May have contained excessive moisture Rutting, some flushing Used drum mixer and vibratory roller	3
AC	1975	Texas Canyon, Arizona IH-10	AR 2000 + Antistrip Producer same as AT (above) Temperature Susceptible West Texas	River gravel with 40% crushed faces River sand	Not tender No rutting Generally performing well Used batch plant and pneumatic roller	0
I	1974	Western Iowa IH-80	85 to 100 Penetration Temperature Susceptible (From same refinery as Asphalt J)	75% Crushed Limestone 25% Field Sand	Tender during and after construction Rutting soon after construction, asphalt concrete base was rutting before surface course was placed Weather was hot during construction Batch plant	4
TA	1979	West of Amarillo Texas IH-40	AC-10 Same as Asphalt H Not Temperature Susceptible	Crushed Limestone Field Sand (somewhat dusty)	Slightly tender - blamed on fine aggregate Apparently water susceptible-blamed on dusty aggregate No rutting Performance satisfactory	1
TS	1979	West of Sonora, Texas IH-10	AC-10 West Central Texas Temperature Susceptible	Crushed Limestone+ Field Sand	Not tender during construction Used temperature susceptible asphalt No rutting	0
WW	1979	Clarkston, Washington SR 129	AC-20 + Antistrip Same as Asphalt F2	Crushed Gravel+ River Sand	Not tender during construction Asphalt contained 0.75% antistrip Performing well, no rutting	1/2
WL	1979	Clarkston, Washington SR 129	AR-4000W + Antistrip Same as Asphalt F1	Crushed Gravel+ River Sand	Somewhat tender during construction Asphalt contained 0.5% antistrip Performing well, no rutting	1 1/2
AO	Sept. 1982	Marietta, Oklahoma SH 32	85-100 pen	Crushed Limestone+ Blow Sand	Not tender during construction Slow setting particularly during hot weather Operated small drum plant over capacity Moisture test yielded none	1
GM	Sept. 1981	North of Glendive, Montana SH 16	120-150 pen	Rounded Gravel with 70% Crushed faces+ River Sand	Somewhat tender during construction No rutting or flushing Some transverse cracking Drum mix plant	2
WD	Sept. 1981	Downtown White Deer, Texas US 60	AC-10 (From same refinery as Asphalt H) Not Temperature Susceptible	Crushed Stone+ Screenings+ Field Sand	Slow setting mix. Can dent with heel after one day but not after 3 weeks Much worse in hot weather Not a problem during construction HMAC moisture ranged from 0.77 to 1.31% Slight rutting after 1 year	1

shall stability, resilient modulus, and indirect tension tests were performed in an attempt to quantify mixture tenderness. According to Hveem et al. (*87*), tenderness of an asphalt mixture will reoccur on heating, or the "slow-setting" quality of an asphalt will reassert itself.

Measurement of resilient modulus at 104 F (40 C) of the newly remolded specimens was accomplished in an attempt to estimate mixture "tenderness" relative to construction difficulties. The resilient modulus versus time testing program was designed to reveal "setting rate" of the asphalts. All specimens were aged and tested at 104 F (40 C). The temperature of 104 F was selected, although it may be outside of the lower extreme of the critical temperature range for pavement tenderness. Yet, it is low enough to allow repeated handling and testing of the specimen without easily inflicting damage.

The first resilient modulus measurement was obtained 90 min after specimen compaction. Seven or eight measurements were taken during the first 24 hours to examine anticipated rapid changes in the newly fabricated specimens. Test frequency was decreased as sample age increased, and tests were continued for a minimum of 3 months.

Water susceptibility of the original core specimens was determined by measuring resilient modulus and Hveem and Marshall stability before-and-after vacuum saturation and soaking of the specimens for 7 days.

Testing of Mixtures From Ongoing Paving Projects

Uncompacted mixtures were obtained at the plant sites and pavement cores were obtained from the finished roadways. Plant-mixed materials were compacted in the laboratory using a Cox (California) kneading compactor and a modified compaction method to produce briquettes containing approximately the same air voids as found in the pavement cores. Mixture properties were determined in accordance with the test plans shown in Figures C2 and C3 (App. C).

Resilient modulus and tensile strength were measured as a function of time (Fig. C2) in order to determine whether a relationship exists between these mixture properties and asphalt setting rate.

In addition, mixture tests were attempted using a blunt-nose penetrometer; test descriptions and results are given in Appendix K.

Test Results and Discussion

Aggregate Properties

A description of the aggregates contained in the test cores is given in Table C1 (App. C). It was necessary to analyze the aggregate properties to determine how much, if any, they contributed to the original mixture problem. Smooth, rounded, nonporous aggregate, an excess of sandsize aggregate and/or small top size aggregate usually contribute to tenderness (*68*). The aggregate gradation from each mixture (Figs. C4 through C14) was compared to the California specification on Figure C15. None of the aggregate gradations intruded the critical mixture region of Figure C15. Hveem stability, a measure of interparticle friction of the aggregate, was relatively low for most of the core samples (Tables C7 and C8).

Most tender mixtures have lower than average Marshall stability (*68*). Low Marshall stability values were obtained on a number of core samples (Tables C7 and C8). However, it is difficult to obtain valid Hveem and Marshall stability data from field cores and such data should be viewed with caution.

The Arizona core samples, AT and AC, contained aggregate of similar grading from the same pit. This is also true of the Washington core samples WW and WL. Core samples TA and TS contained aggregates of comparable characteristics, meeting the same specifications but from different regions of Texas. Highway department personnel attributed the slight tenderness exhibited by this mixture, in part, to the fine aggregate in core sample TA.

Mixtures TA and TS illustrate the fact that mixture tenderness can be experienced while using an asphalt of extremely low temperature susceptibility (TA) and, conversely, that a highly temperature susceptible asphalt may perform satisfactorily (TS) when quality aggregate, construction techniques, and compaction equipment are employed.

According to the state highway engineers supplying the specimens, aggregate gradation adjustments were, in most cases, made during construction in an attempt to alleviate the tenderness problem. Furthermore, identical aggregates with similar gradations had been successfully used in paving mixtures with asphalts from different refineries or asphalts produced at a different time.

Asphalt Properties

Determination of asphalt consistency as a function of temperature and its relationship to pavement construction and early life performance was the primary emphasis of this subtask of the study. Properties of asphalts extracted and recovered from cores obtained from existing pavements is presented on Table C2. Original properties of these asphalts are given in Tables 9, 10, 11, and 12. Table C3 gives properties of the original asphalts used in the ongoing paving projects.

Based on user comments about the character of these mixtures in the field, there appears to be some relationship between viscosity at 140 F (60 C) and pavement tenderness. When grouped by state or asphalt grade, it is readily seen that, in each case, the recovered asphalts with the lower viscosities at 140 F were involved in the tender mixtures. This is not surprising as 140 F is near the temperature range where tenderness is expected. (Be reminded that mixture TA contained Asphalt H which has been shown to have low temperature susceptibility and that the slight tenderness exhibited by this mixture during construction was attributed to the fine aggregate and, further, that no rutting or other short-term pavement performance problems became evident.) Observation of these data shows that none of the other asphalt properties consistently show direct relationships with mixture tenderness.

Several parameters describing temperature susceptibility over various temperature ranges were computed from the asphalt properties and are given in Tables C4 and C5. Each temperature susceptibility parameter was compared with the subjective "mixture tenderness ratings," discussed earlier, to investigate the possibility of any correlations. Rather weak, yet consistent relationships are shown by VTS (77-140 F) (25-60 C), PVN (77-275 F) (25-135 C), PVN′ (77-140 F) (25-60 C) and PTS or PI (Eq. D1). Plots of these values versus mixture tenderness rating are presented in Figures 27 through 30. If there is a strong correlation between asphalt temperature susceptibility and mixture tendernesses, it was for the most part, masked by variations in aggregate properties and/or construction techniques. Data obtained from an uncontrolled experiment will naturally involve considerable variability and be of limited reliability.

Although no strong correlations are apparent in the data presented above, based on discussion with state highway con-

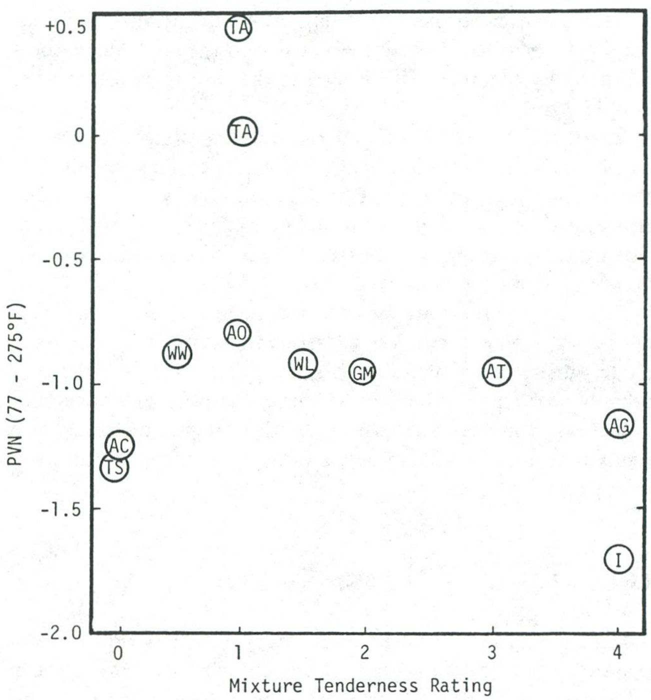


Figure 27. Relationship between mixture tenderness and penetration-viscosity number (77-275 F).

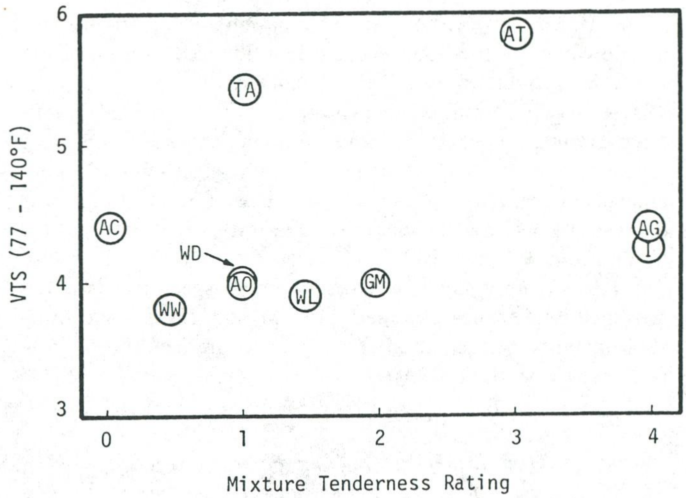


Figure 28. Relationship between mixture tenderness and viscosity-temperature susceptibility (77-140 F).

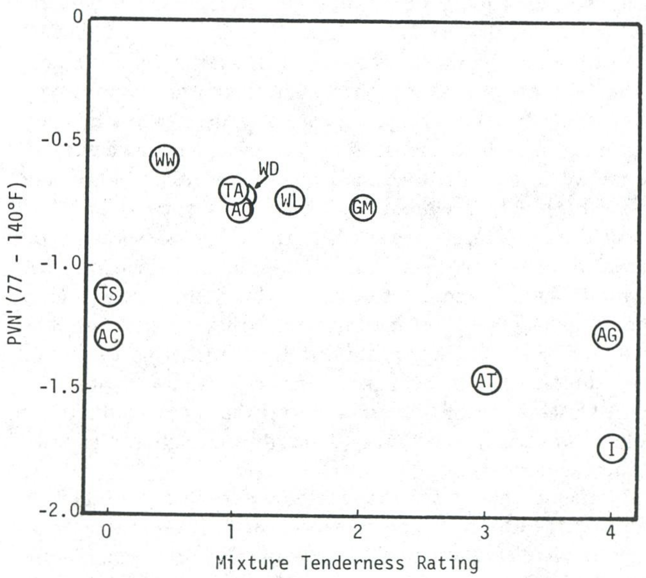


Figure 29. Relationship between mixture tenderness and penetration-viscosity number (77-140 F).

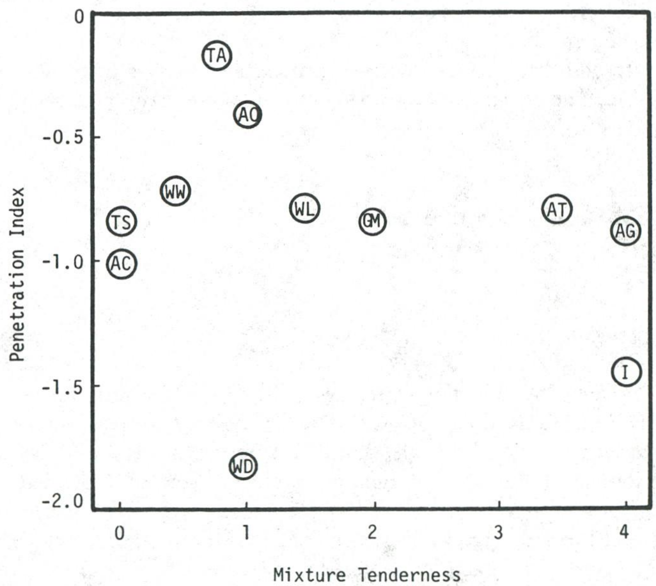


Figure 30. Relationship between mixture tenderness and penetration index (Eq. 1, App. D).

struction and materials engineers, the more highly temperature susceptible asphalts are more often troublesome. These binders can, however, be used by making adjustments in mix design and/or construction techniques. Several engineers believe that slow-setting asphalts perform satisfactorily and some say are even superior, once they set up. The highly temperature susceptible binder (Asphalt C) has been used in blends with other binders to dilute its ability to cause construction and short-term performance problems and to improve the long-term performance of the asphalt with which it is blended.

Lund and Wilson (*88*) developed a formula to determine the difference in the actual change in asphalt viscosity during mixing and placement and that predicted by the rolling thin film oven test (RTFOT):

$$C = \left[\frac{R - A}{B - A}\right] (100\%)$$

where:

A = absolute viscosity of the original asphalt at 140 F;
B = absolute viscosity of the RTFOT residue at 140 F; and
R = absolute viscosity of the asphalt recovered from mixture at 140 F.

When C equals 100 percent, RTFOT accurately predicts the actual viscosity increase that occurs in the field. When C is less than 100 percent, less hardening occurred in the field than predicted by RFTOT and vice versa. The authors (*88*) stated that based on field observations of paving projects, no tenderness problems were experienced when C values were above 50 percent, some tenderness problems were experienced when C values ranged from 30 to 50 percent, and tenderness problems were always experienced when C values were less than 30 percent.

Values for C were computed for the field projects studied herein and are presented in Table C6, Appendix C. Figure 31 shows that for these field projects, there is no correlation between C value and mixture tenderness.

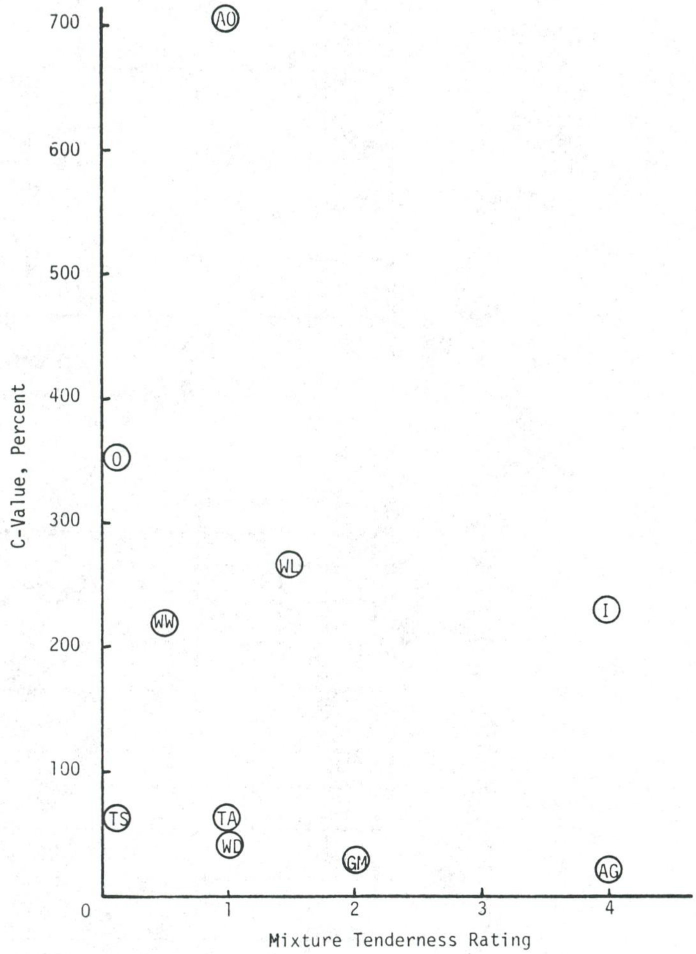


Figure 31. C-values for asphalts from field projects versus tenderness rating.

Mixture Properties

The objectives of this segment of the research were to define the properties of the 11 paving mixtures and determine which properties, if any, relate to mixture tenderness and/or setting qualities.

Resilient moduli of the core specimens were measured at several temperatures to define "mixture" temperature susceptibility and to observe mixture stiffness at the higher temperatures. Results of these tests are provided in Tables C7 and C8 and are plotted in Figures 32 through 36. Field mixtures AT and AC were plotted together (Fig. 32) because they contain similar materials; mixture AG was included because it was obtained from the same state and contained somewhat similar aggregate. Mixtures TA, TS, and I were plotted together (Fig. 33) because they are the only three mixtures containing crushed rock. Mixtures WW and WL were plotted together (Fig. 34) because they contain very similar materials from identical sources. Figures 35 and 36 contain data from cores and laboratory-compacted specimens from the ongoing construction projects. No consistent correlations between slope of the resilient modulus versus temperature curves and mixture tenderness were evident. However, it appears that pavement cores with resilient modulus values (at 77 F) below 350,000 psi experienced tenderness problems during and/or shortly after construction.

Under controlled conditions the resilient modulus device has the potential for recognizing tender mixes and defining mixture temperature susceptibility. Figure 37 shows resilient modulus test results from laboratory-compacted specimens of subrounded gravel and crushed limestone with a single AC-10 asphalt (*89*). Standard sieves were used to separate the aggregate into fractions from ¾-in. to minus No. 200 mesh. The various aggregate sizes were recombined in accordance with ASTM D-3515-77 5A grading specification. Thus, the two aggregates had the same gradation. Asphalt-aggregate mixtures were compacted using the gyratory-shear molding press. Figure 37 illustrates the dependence of resilient modulus on the aggregate characteristics. The round, smooth particles of the gravel aggregate produce less interparticle friction to aid in resisting shear stresses. The rough, angular particles of the crushed limestone produce considerable interparticle friction which is manifested by the higher resilient moduli at higher temperatures. The overall temperature susceptibility of the gravel mixture is greater than that of the limestone mixture. Furthermore, by observing the slope of the curves at any temperature in Figure 37, temperature susceptibility of the gravel mixture is seen to be greater than that of the limestone. As discussed earlier, the remolding procedure was designed to recreate tender mixtures, compact them while in the tender state, and conduct basic tests before and during setting of the mixture. This was to determine which, if any, of the test methods would detect relative tenderness or indicate mixture properties that relate to tenderness.

In Figures 38, 39 and 40, resilient moduli at 104 F (40 C) as a function of time are plotted for the remolded field mixtures aged at 104 F. In each figure, the tender mixtures have comparatively lower values of resilient modulus during the first 8 hours, and in most cases they remained lower throughout the

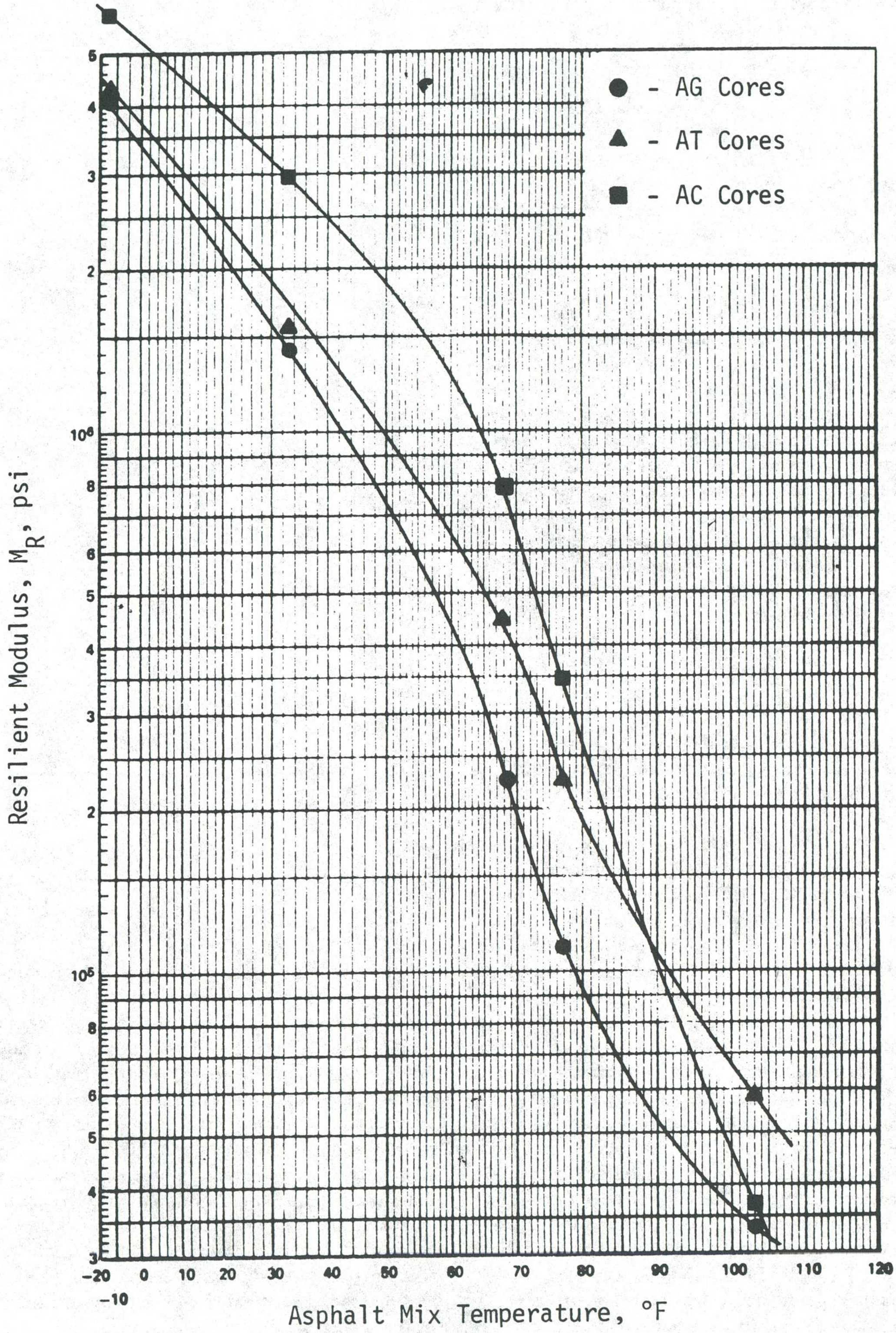


Figure 32. Resilient modulus of Arizona cores as a function of temperature.

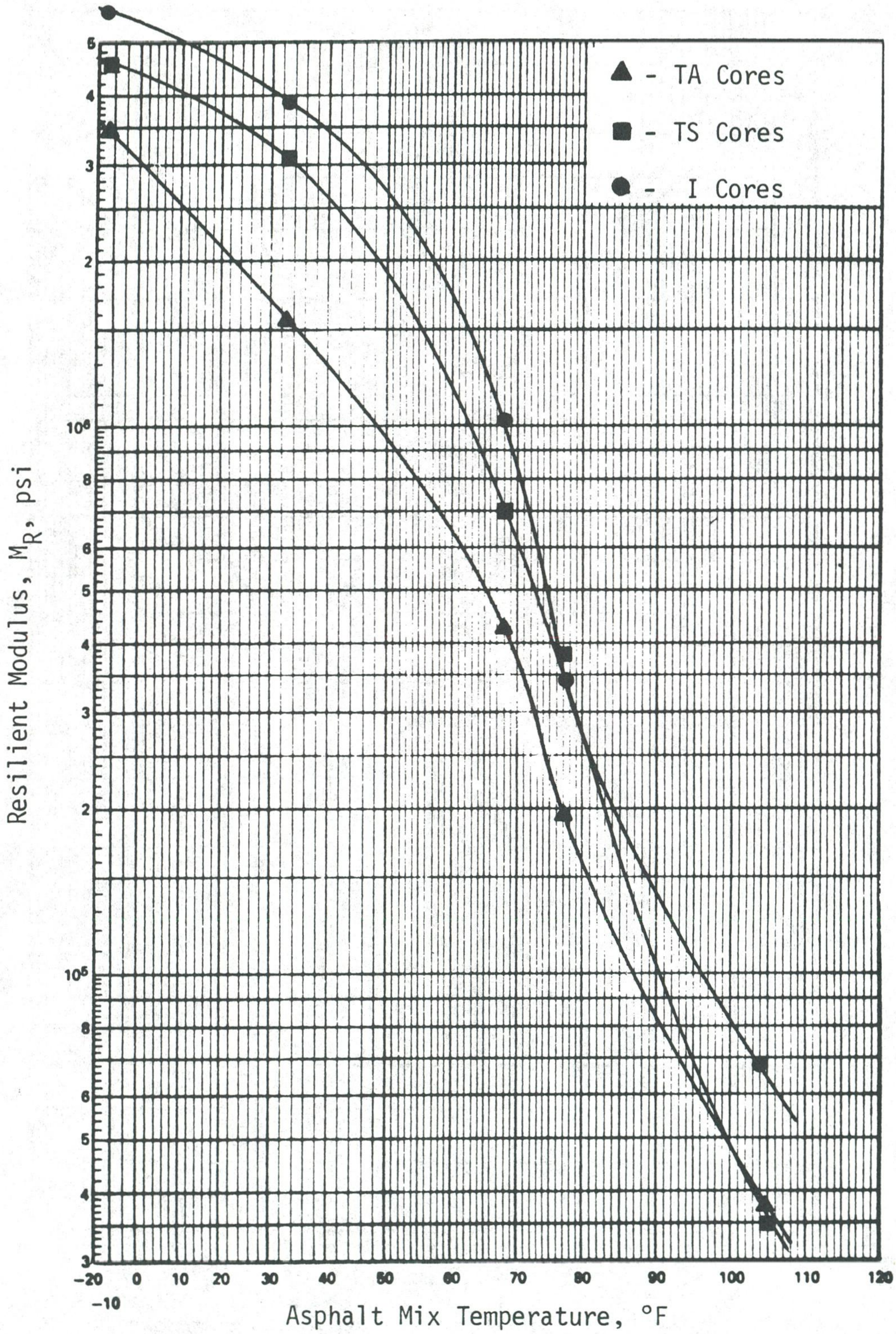


Figure 33. Resilient modulus of Texas and Iowa cores as a function of temperature.

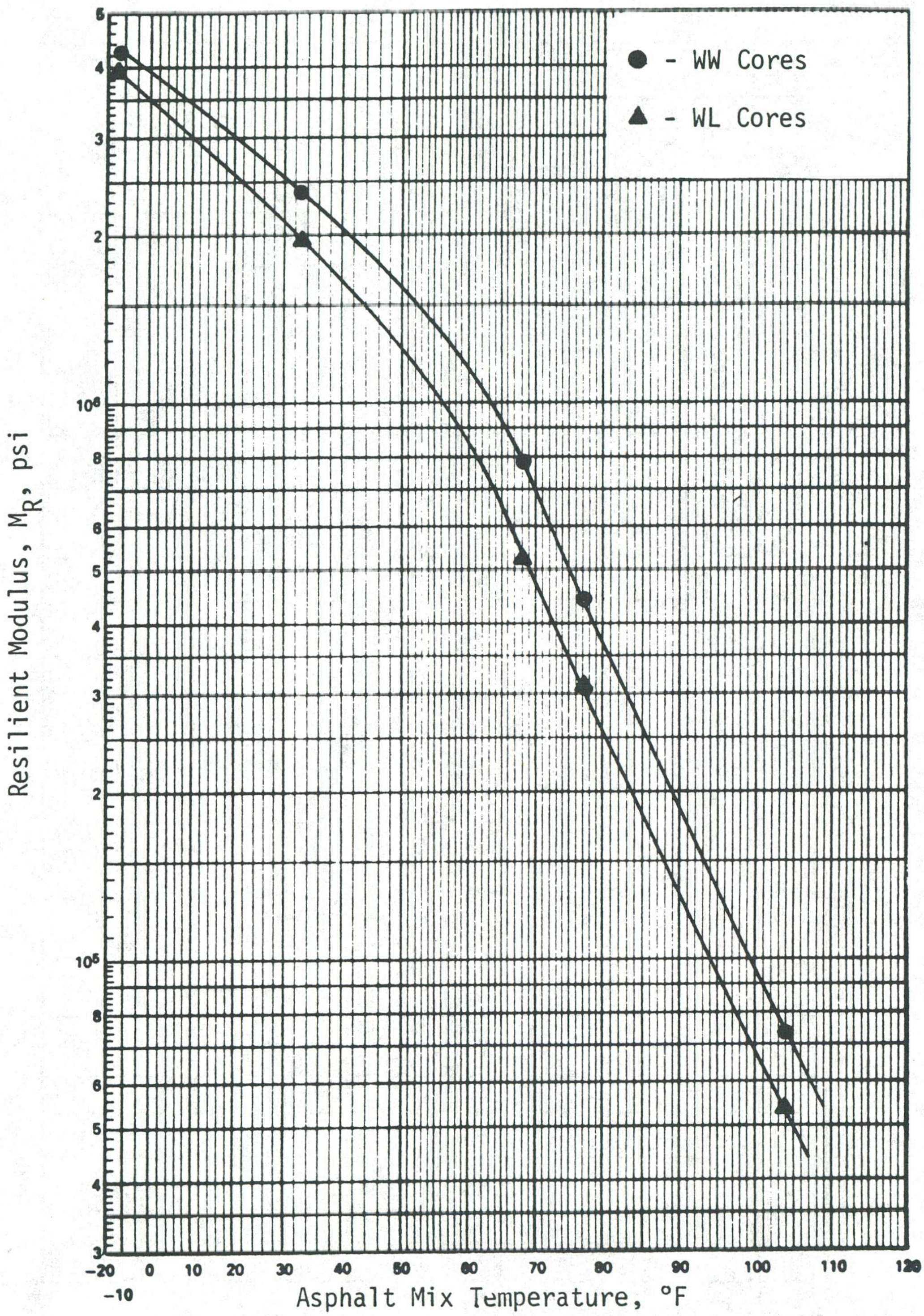


Figure 34. Resilient modulus of Washington cores as a function of temperature.

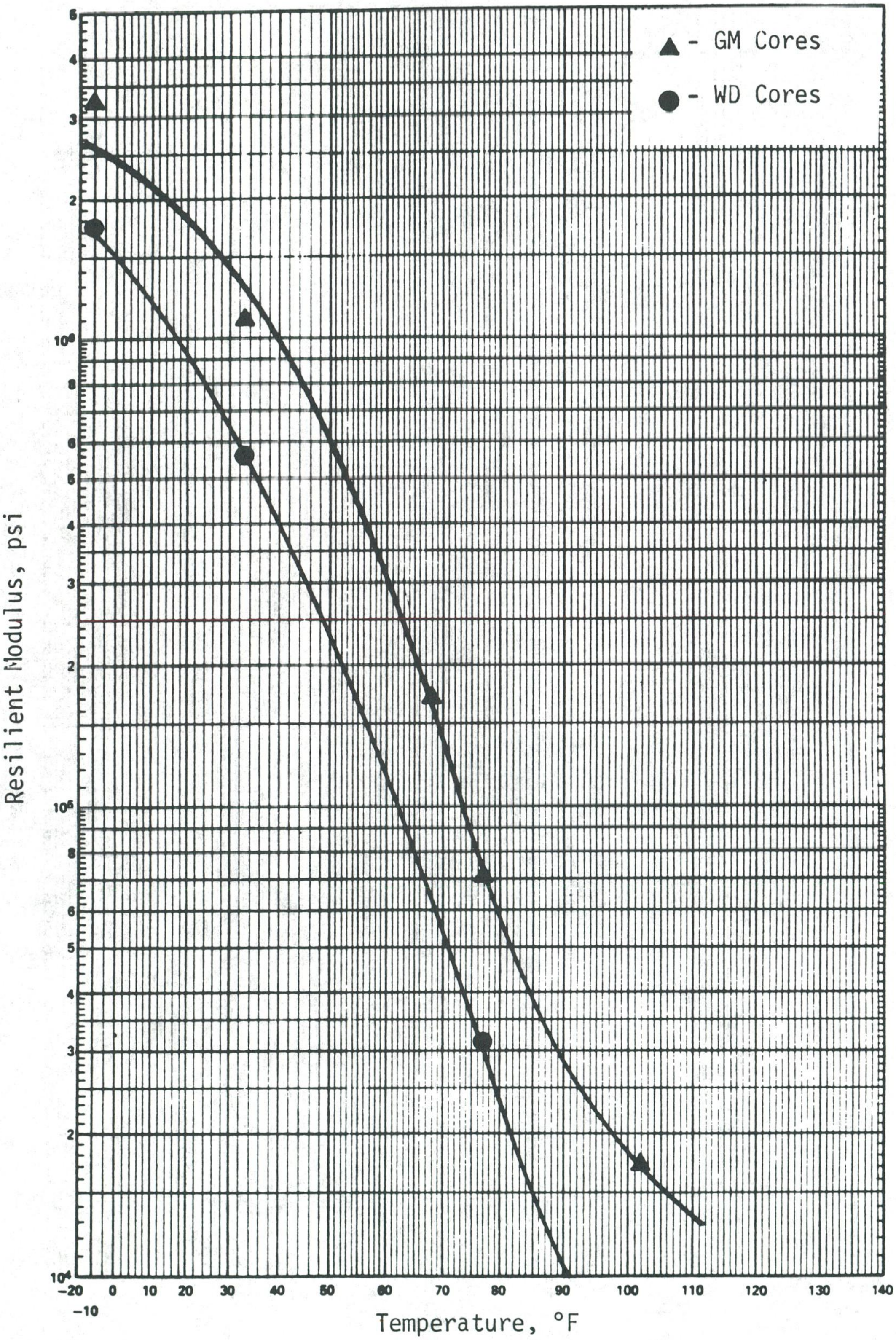


Figure 35. Resilient modulus as a function of temperature for cores from ongoing construction projects.

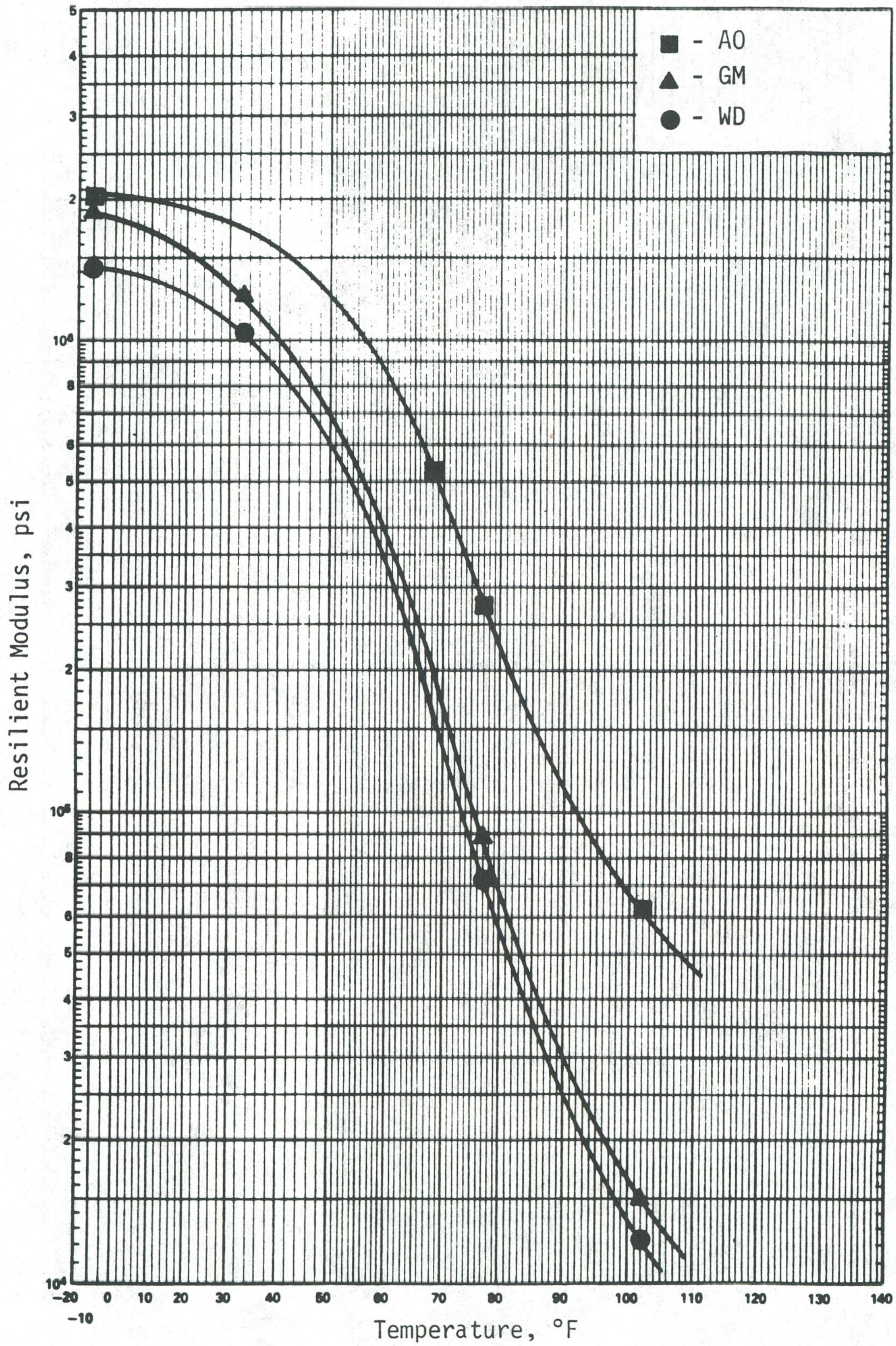


Figure 36. Resilient modulus as a function of temperature for field mixed/laboratory compacted mixtures from ongoing construction projects.

experiment. The reasons for the decrease in resilient modulus during the first 8 hours of specimen life have not been defined. Stress relaxation is a potential cause. It is suggested that when stresses imparted to the specimens by compaction and cooling are dissipated, specimen stiffness would diminish. Stiffness of the specimens begins to increase almost immediately after the minima are encountered. It is postulated that early in the life of the compacted mixtures the rate of increase in resilient modulus depends on setting rate (structuring or thixotropic characteristics) of the asphalts and, later, on age-hardening rate of the asphalt, both of which are related to the conditioning temperature.

Resilient modulus at 104 F, 90 min after remolding, is compared to the subjective mixture tenderness rating in Figure 41. Figure 42 depicts the relationship between resilient modulus of the original cores and the remolded specimens at an age of 2 weeks and mixture tenderness. In each case, resilient modulus decreases with increased mixture tenderness; however, the rate of decrease diminishes with time.

Resilient modulus versus time data for the field-mixed and laboratory-compacted mixtures aged at 140 F is presented in Table C9 and plotted in Figure 43. The comparatively low resilient moduli are a result of the high air void content of these mixtures. Recall that compactive effort was reduced to produce laboratory specimens with air void contents approximately the same as those obtained under field conditions. Mixture GM was tender during construction, but was very tough shortly thereafter. Mixture WD was only slightly tender during construction, but appeared to be slow setting, requiring 3 or 4 weeks to "toughen up." On the basis of these field tests, it was impossible to relate setting rate with resilient modulus as a function of time because too many variables were involved.

Figure 43 shows that mixture GM is slightly stiffer than mixture WD and that their rate of stiffening is about the same when aged at 140 F for more than 3 months. The Oregon material (described in App. H) exhibits the highest resilient modulus of the four samples tested; however, the rate of stiffening is about the same as mixtures GM and WD. In the field, the Oregon mixture was neither tender nor slow setting. The contractor claimed that mixture A0 was slow setting; however, when aged at 140 F, resilient modulus increased notably faster than the other three mixtures.

Resilient moduli of newly compacted laboratory specimens offer promise as a method of identifying tender mixtures prior to field construction. Resilient modulus as a function of time may be helpful in predicting short-term performance. Specified minimum values of resilient modulus will depend on viscosity of the asphalt, as evidenced in Figure 39, where the harder grade asphalts exhibited notably stiffer mixtures.

The splitting tensile test (indirect tension) performed at 77 F (25 C) and a loading rate of 2 in. per minute (5.1 cm/min) was employed to examine tensile properties of the specimens 90 min after remolding. Tensile strength and secant modulus from the splitting tensile test are compared with the mixture tenderness rating in Figures 44 and 45. Each figure shows increasing mixture tenderness with decreasing tensile properties. The influence of asphalt viscosity is shown by the higher tensile strengths of mixtures WW and WL. Results of the splitting tensile test on newly fabricated asphalt paving mixtures appears to be an excellent predictor of mixture tenderness. Tensile strength at 77 F of gyratory molded specimens should exceed 125 psi if tenderness problems are to be avoided.

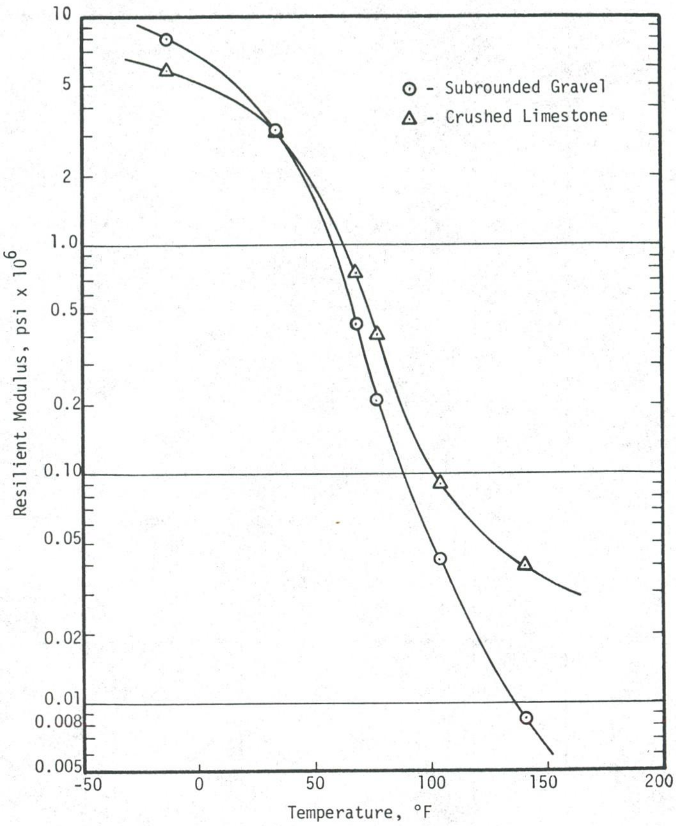


Figure 37. Resilient modulus of laboratory compacted specimens as a function of temperature.

A series of indirect tension tests were performed at four different temperatures on the laboratory-compacted field mixtures from the ongoing field projects. These tests were performed primarily to determine the maximum temperature at which tensile properties could be effectively measured using the indirect method. When these data were plotted (Fig. 46), the order and slope of the three curves reflected the order of the temperature susceptibility of the asphalt cements. That is, at temperatures below 175 F, those mixtures containing the most temperature susceptible asphalts exhibited the greatest increase in tensile strength.

On the basis of the test series described above, a temperature of 104 F (40 C) was selected as the maximum, because above this temperature tensile strength became quite low. Tensile strength at 104 F of the four field mixtures was measured after different periods of aging at 140 F (60 C) (Table C10). The results (Fig. 47) show the same respective relationships as shown by the resilient modulus tests. Differences in setting rate observed in the field were not apparent in these data.

Marshall stability of original pavement cores and remolded mixtures 90 min after compacting are compared to the mixture tenderness rating in Figure 48. No correlations are apparent. The lack of precision inherent to the Marshall test may have contributed to the inconclusive results. Additionally, the Marshall test possibly does not measure mixture properties pertinent to tenderness. Limited quantities of certain samples prohibited Marshall testing of remolded mixtures AG and AC.

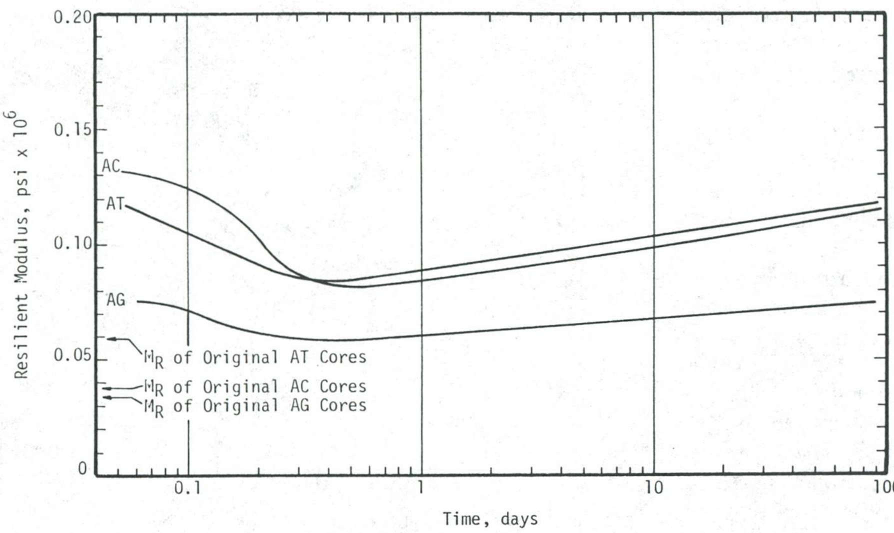


Figure 38. Resilient modulus of remolded Arizona specimens versus time. Each curve represents an average of 2 or 3 specimens.

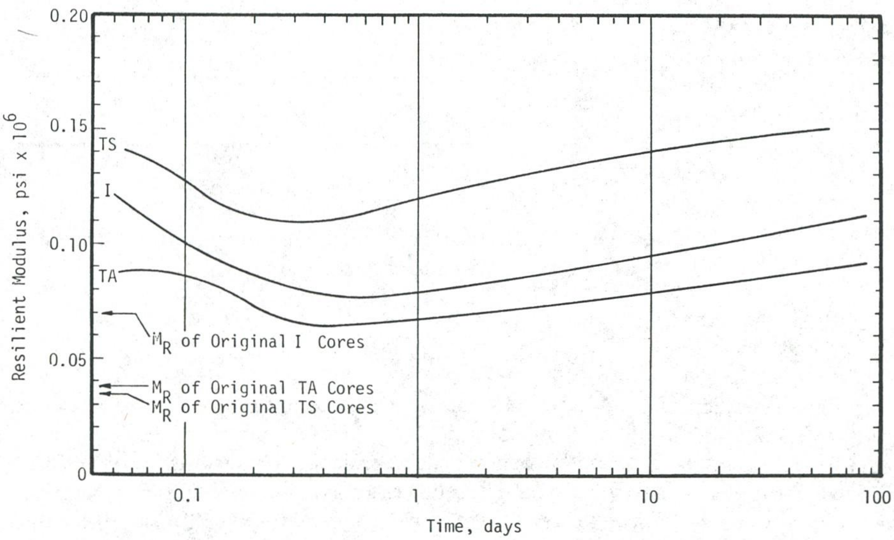


Figure 39. Resilient modulus of remolded Texas and Iowa specimens versus time. Each curve represents an average of 2 or 3 specimens.

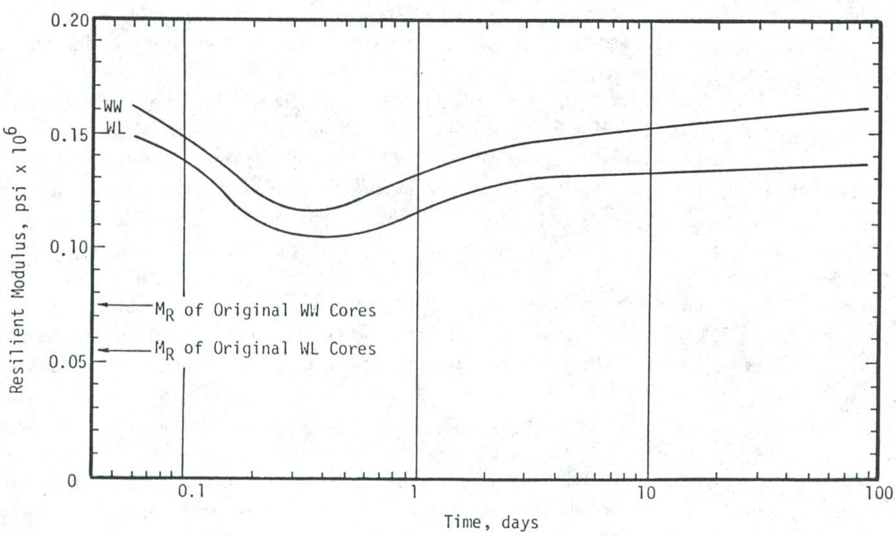


Figure 40. Resilient modulus of remolded Washington specimens versus time. Each curve represents an average of 2 or 3 specimens.

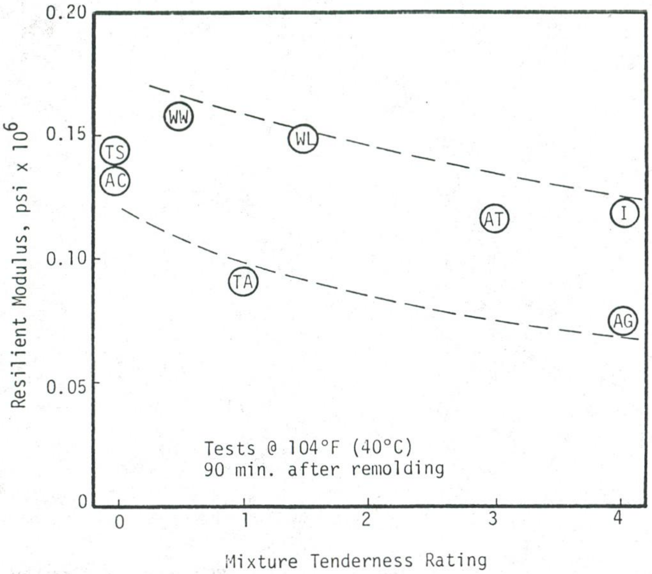


Figure 41. Relationship between mixture tenderness and resilient modulus.

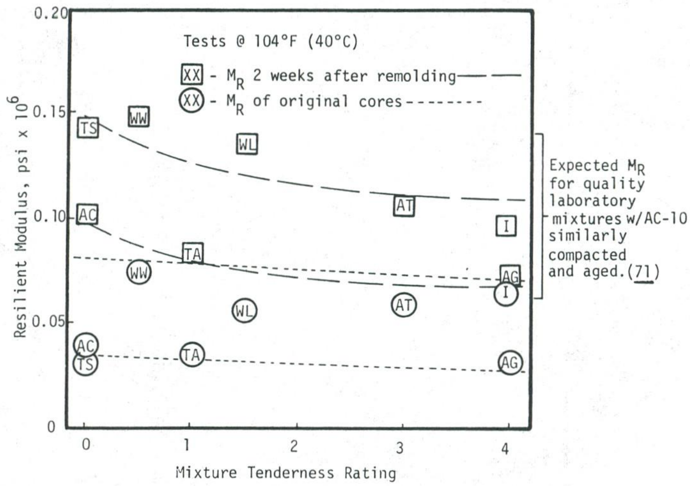


Figure 42. Relationship between mixture tenderness and resilient modulus of original cores and remolded specimens at two weeks of age.

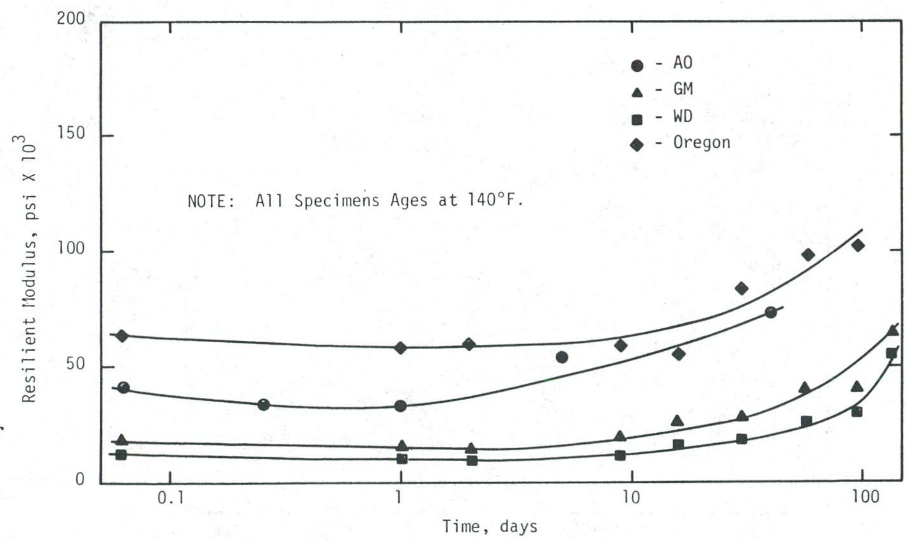


Figure 43. Resilient modulus at 104 F of field mixed/laboratory compacted specimens versus time. Each point represents an average of 3 or 4 specimens.

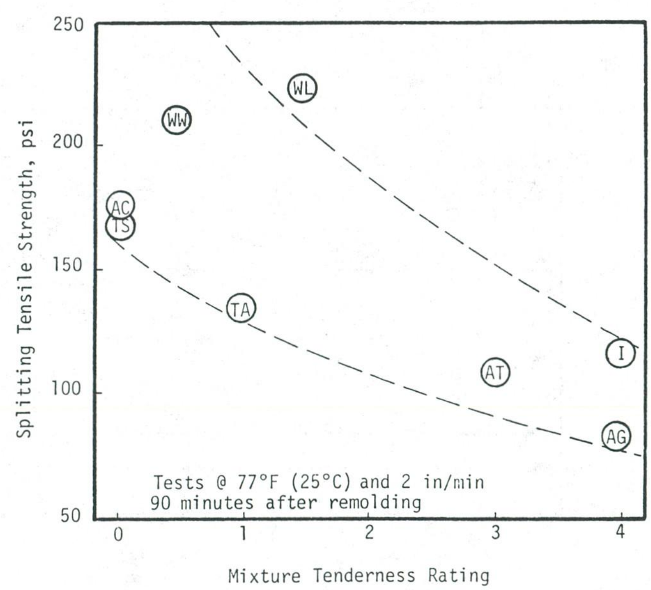


Figure 44. Relationship between mixture tenderness and indirect tensile strength.

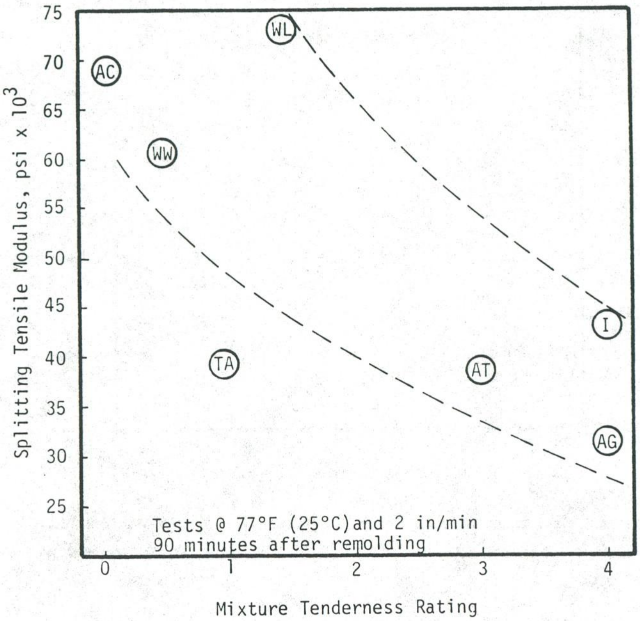


Figure 45. Relationship between mixture tenderness and secant modulus from the indirect tensile test.

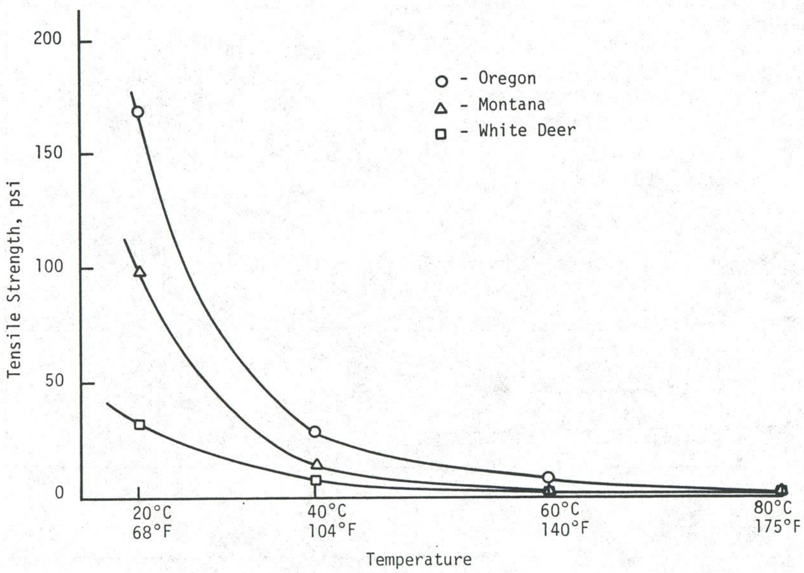


Figure 46. Tensile strength of laboratory-compacted field mixtures as a function of temperature.

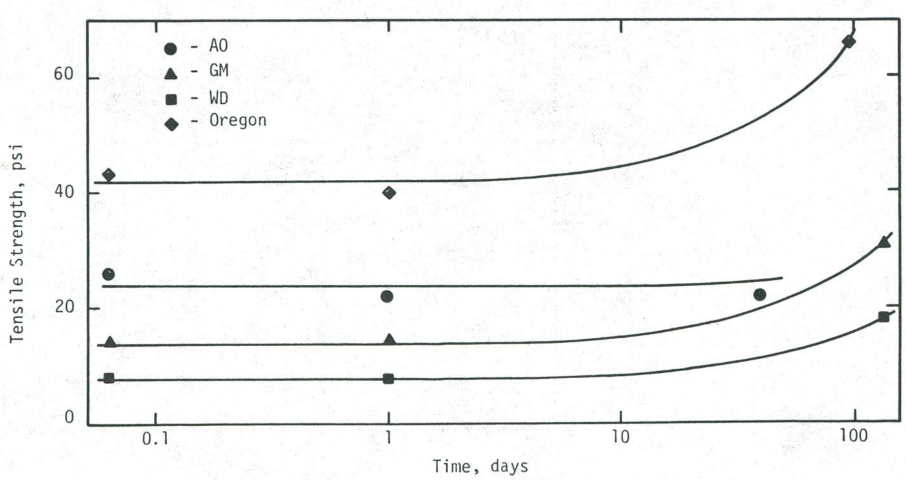


Figure 47. Effects of aging at 140 F on tensile strength at 104 F of field mixed/ laboratory compacted specimens. Each point represents an average of 3 specimens.

Air void contents of the remolded specimens were unrealistically low as a result of the very efficient compactive forces generated by the gyratory-shear molding press. For this reason, resilient modulus, tensile properties, and Marshall stability indicated that the remolded specimens were of significantly higher quality than the original pavement cores. Less compactive effort would have produced samples more sensitive to binder properties and, possibly, would have shown more contrast in quality of tender and nontender mixtures.

Considering the nonhomogeneity of these field specimens and the uncertainty associated with the subjective rating of tenderness, any conclusions drawn from these experiments should be used with caution. Nevertheless, the relationships are mutually supportive and practical. Although preliminary in nature, these test results give strong evidence that resilient modulus and tensile properties, particularly of freshly compacted specimens, may be useful in predicting tender mixtures. It should be pointed out that values obtained from these tests depend on grade (i.e., viscosity) of the asphalt. Notice that mixtures WW and WL (which contain harder grade asphalts) exhibit comparatively large values of strength and stiffness.

Water susceptibility does not appear to be directly related to tenderness; however, because tender mixtures are often not well compacted, water will enter the mat and cause problems that otherwise may not have occurred (*68*). Therefore, tests were performed to evaluate water susceptibility as an indirect result of tenderness. Determination of water susceptibility was given the lowest priority in this test program. Therefore, those mixtures with insufficient quantities to complete all phases of testing were eliminated from the water susceptibility phase. Mixtures AG, AT, and AC were in this category.

A summary of original pavement core properties before and after vacuum saturation and soaking in water for 7 days is given in Table C11. Ratios to indicate relative water susceptibility have been computed by dividing values for resilient modulus and Hveem and Marshall stabilities after moisture treatment by corresponding values before treatment. The ratios are presented in Table C12. The data are scant but there is apparently no correlation between water susceptibility and mixture tenderness. Analysis of these data shows that generally moisture damage increases with air void content of the original pavement cores. Although the correlation is rather weak, it is certainly not surprising.

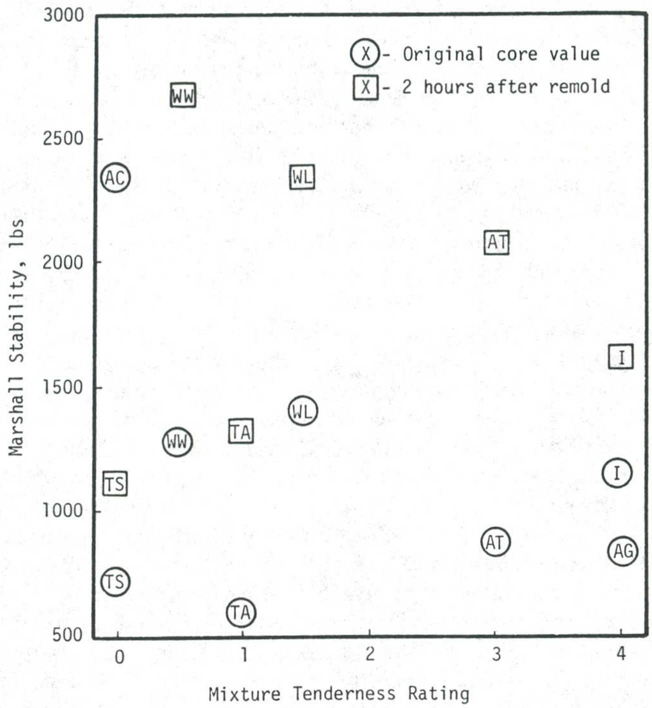


Figure 48. Relationship between mixture tenderness and Marshall stability of original cores and remolded mixtures.

Summary of Field-Laboratory Test Program

The higher air void contents of cores AG and AT, when compared to AC (Table C6), may be a result of tenderness during construction. However, it should be pointed out that the pavement AC was 5 years old. Prolonged traffic action no doubt densified pavement AC to some extent. Generally, the AC cores exhibited values of strength, stiffness, and stability significantly higher than corresponding values for AG and AT. Inasmuch as all three mixtures contained asphalts with similar temperature susceptibilities (Table C4), none of the differences in mixture properties or workability during construction may be attributed to variations in asphalt temperature susceptibility.

Mixture I exhibited tenderness during construction and instability during early pavement life. It contained an 85–100 penetration grade asphalt from the producer of Asphalt J. This is a highly temperature susceptible asphalt, quite low in viscosity at 140 F, and fairly resistant to hardening. The aggregate was partially crushed stone with a reasonably satisfactory gradation. The pavement was 6 years of age when sampled and tested. It had a relatively low air void content, which is likely due to its exposure to traffic, which, consequently, resulted in comparatively high values of strength, stiffness, and stability.

Mixtures TA and TS contained crushed aggregates passing the same specifications. Mixture TA contained Asphalt H which has low temperature susceptibility, is resistant to hardening, and has been associated with slow-setting mixtures. The mixture was described as slightly tender during construction. Mixture TS contained a highly temperature susceptible asphalt and was not tender during or after construction. The asphalt cement in mixture TS is usually furnished near the lower end of the 140 F (60 C) viscosity specification to meet the 77 F penetration specification; yet the asphalt recovered from mixture TS was harder than that recovered from mixture TA. Therefore, it may be assumed that the asphalt in mixture TS is hardened more during construction than the asphalt in mixture TA.

Mixtures WW and WL contained crushed gravel of virtually identical characteristics with similar quantities of AC-20 and AR 4000W asphalts, respectively. Both asphalts are from the same refinery. The asphalts are fairly temperature susceptible, and the only fundamental difference in the two asphalts is that the AC-20 is slightly harder. The slightly higher viscosity of the AC-20 was apparently just enough to eliminate the slight tenderness observed during construction with the AR 4000W. Another noteworthy difference in the character of these asphalts can be observed in Table C4. Although the original Asphalts

F1 and F2 have similar viscosities, the properties of the extracted and recovered asphalts reveal significantly greater hardening by Asphalt F2, which was used in the less tender mixture WW.

Mixture AO was described by the contractor as often tender during construction and slow setting thereafter, particularly during warm weather and when placed in lifts of 2-in. or more. He further stated, however, that the breakdown roller could operate close behind the paving machine. At the time of the visit by the author, the weather was cool (70 F) and the contractor was placing a lift approximately 1-in. in thickness. As a result, no compaction problems were evident, and the freshly compacted mix was not easily dented with the heel or scuffed with power steering. Table C2 shows that the 120–150 pen asphalt in this mixture had hardened significantly, which likely contributed to the lack of tenderness observed during construction. The subrounded particles of the blow sand used in this mix (Table 14) is most likely the chief contributor when tenderness is observed.

Mixture GM was placed in a 1½-in. lift. The contractor claimed it was very difficult to compact at normal compaction temperatures. Low viscosity asphalt (Table C2) in concert with subrounded aggregate particles will often produce tenderness during construction. A vibratory roller was used for breakdown compaction. Final compaction was accomplished using a steel wheel roller up to 2 hours behind the paver. No pneumatic rollers were used. (Note that the air void content of the cores was 14 percent.) The mixture was, however, fast-setting as it became quite hard as soon as it reached ambient temperature (90 F); that is, it could not be dented with the heel of one's shoe. After 1 year in service, mixture GM was in excellent condition with no rutting or flushing. There were, however, a few random transverse cracks.

Relationships between mixture tenderness and asphalt temperature susceptibility are at best weak; nevertheless, they do appear to exist. However, a relationship between mixture tenderness and hardening resistance of the asphalt also appears to exist.

This agrees with findings of other researchers (*78*). Sufficient data to illustrate this point were not generated in this experiment.

Supplemental Data

In order to supplement these data, observations were made and materials were obtained during construction of test pavements at Dickens and Dumas, Texas. Seven test pavements were installed at each location. Asphalts (AC-10 and/or AC-20) from each of five different refineries were employed. An attempt was made to hold all other variables (aggregate type and gradation, equipment, temperatures, etc.) constant during construction. Temperature susceptibility of the asphalts used in this study had about the same range of values as the extremes for the United States. Data from these two test pavements are presented and discussed in Appendix J.

LABORATORY TESTING OF ASPHALT PAVING MIXTURES

Based on the literature review and research previously completed on this project, a testing program was formulated to investigate those mixture variables which were identified as having the most influence on pavement construction operations and short-term performance. The variables included in the test program are:

1. Asphalt cement source (5 sources).
2. Asphalt cement grade (3 grades).
3. Aggregate gradation (low and high sand content).
4. Filler content (low and high quantities).
5. Type of aggregate (subrounded river gravel and crushed limestone).
6. Asphalt content (optimum plus or minus 0.5 percentage points).
7. Air void content (6 to 8 percent, plus or minus).

Test Program

The test program was structured to identify measurable properties of mixtures which could be related to observed pavement tenderness problems during compaction and setting properties of the mixture during the early life of the pavement. Resilient modulus and indirect tensile (diametral) tests were used in the test program because they have proven to be tests which are the most sensitive to asphalt properties in paving mixtures.

A test temperature of 104 F was selected as a compromise between the ability of existing test equipment to measure properties of mixtures at elevated temperatures associated with compaction (175–275 F) and the in-service environment (100 to 165 F). The maximum temperatures at which resilient modulus and tensile strength can be reliably measured is about 100 F. A temperature of 104 F, or 40 C, has been selected and used throughout the test program.

A load duration of 0.1 sec was selected for resilient modulus testing. This length of time reasonably approximates the time period a roller contacts a given point on the pavement. Tensile tests were performed at deformation rates of 2 in. per minute to simulate and allow the use of Marshall testing equipment.

Materials

Appendix L describes the details of the test program and the materials used, and presents individual and averaged test results for each of the three subprograms. Five sources and three grades of asphalt were selected to represent asphalts with different physical-chemical properties:

1. High and low temperature susceptibility.
2. High and low viscosity at 140 F.
3. High and low hardening after TFOT test.
4. High and low asphaltene contents.

Asphalts B1, B2, B3, C, H, K, and L1 were selected. Physical and chemical properties are given in Tables 9 and 16. The rating shown in Table 8 indicates that several of these asphalts have been associated with tender pavements.

Results

Appendix L contains an extended discussion of test results. A summary is presented in the following and grouped to illustrate the effect of various mixture variables on the properties of paving mixtures.

Asphalt Source

Figures 49 and 50 show the relationship between resilient modulus and tenderness rating of the asphalt and tensile strength and tenderness rating of the asphalt, respectively. The mixtures were prepared at design asphalt content using subrounded river gravel, with low filler content, high sand content, and relatively high air voids. This combination of variables is known to produce pavements that are difficult to compact. If a tenderness rating of 2 or below is considered acceptable, the resilient modulus of the high void mixtures at 104 F should be above about 7,000 psi and have a tensile strength at 104 F above about 5 psi.

Data contained in Appendix L indicate a possible relationship between resilient modulus and tensile strength. Figure 51 indicates the relationship for samples tested at 104 F 24 hours after mixing. Because a relationship is evident, it is reasonable to assume that these two tests measure about the same mixture property.

Time Effects

Figures 52 and 53 illustrate the influence of time after mixing on the properties of mixtures prepared with different asphalts. All of these mixtures contained subrounded gravel, low filler contents, high sand contents, design asphalt contents, and high air voids. These combinations of materials should be expected to produce tender mixtures.

Resilient modulus and tensile strength gains with time may be associated with (1) setting of the asphalt, (2) asphalt-aggregate physical-chemical interactions, and/or (3) hardening of the asphalt due to oxidation, volatilization, etc. Relatively small gains in resilient modulus and tensile strength are associated with asphalts B1, C, and H. These asphalts have been associated with tender pavements both during and after construction. These asphalts have low asphaltene contents.

Relatively large gains in resilient modulus and tensile strength are associated with Asphalts B3, C, and L1. These asphalts are seldom associated with tender pavements.

Figure 52 indicates that 24-hour resilient modulus values at 104 F less than about 5,000 to 6,000 psi are associated with mixtures that contain asphalts that are associated with tender mixes. Figure 53 indicates that tensile strength at 24 hours less than about 4 or 5 psi are associated with mixes that contain asphalts that are associated with tender mixes. These data supplement the findings illustrated in Figures 49 and 50.

Water Susceptibility

Limited tests were performed to determine water-susceptibility. Results from the Lottman procedure (*90, 91*) on mixtures containing gravel aggregates are shown in Figure 54. Asphalt H is more water susceptible than the other asphalts, but does not produce unacceptable mixtures. Literature suggests that asphalt source and grade will influence the resistance of a given mixture to water damage.

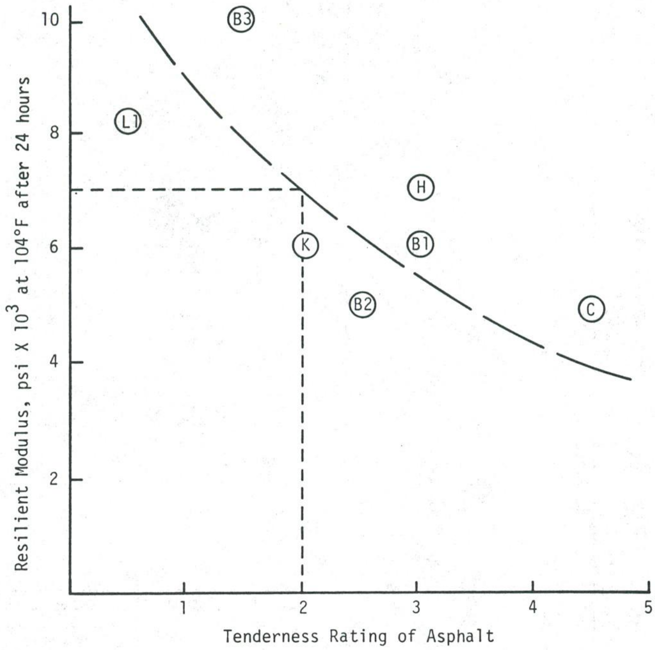


Figure 49. Relationship between resilient modulus and tenderness rating of asphalt—Test Plan a.

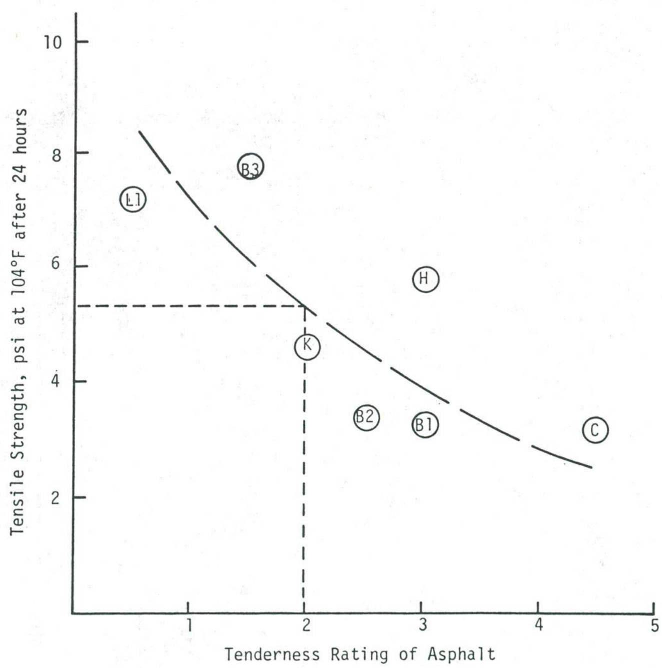


Figure 50. Relationship between tensile strength and tenderness rating of asphalt—Test Plan a.

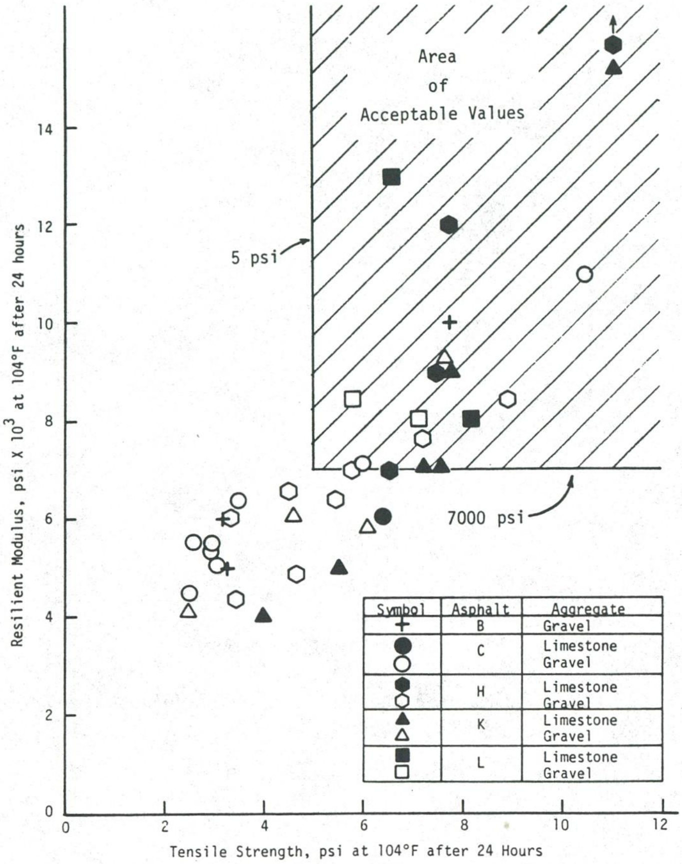


Figure 51. Relationship between resilient modulus and tensile strength determined at 104 F—Test Plan a.

Mixture Temperature Susceptibility

Limited data collected in this study do not allow a reliable relationship to be developed between mixture temperature susceptibility as measured by resilient modulus and asphalt temperature susceptibility as measured by the indices previously discussed. A relationship between mixture and asphalt temperature susceptibility should not necessarily be expected as mixture temperature susceptibility is determined at 104 F and below, while most measures of asphalt temperature susceptibility are determined at 77 F and above.

AGGREGATE TYPE AND GRADATION

Figures 55, 56 and 57 illustrate the effect of aggregate type, filler content, and sand content on mixture properties. The following general trends are evident from a review of these figures.

Increasing the filler content increased the tensile strength of mixtures containing subrounded river gravel. Larger tensile strength increases are noted for those mixtures containing low sand contents as opposed to high sand contents. If it is assumed that tensile strengths greater than 4 to 5 psi are required to produce mixtures that are not tender, it is evident that fillers can be used in all the gravel mixtures investigated to improve the performance.

Increases in tensile strength with increased filler contents have also been noted for mixtures containing limestone aggregates. However, the magnitude of this increase is not as large when compared with the gravel mixture.

Comparisons between mixtures with low and high sand contents can also be made from these data. For mixtures containing gravel aggregate with low filler contents, an increase in tensile strength was noted with an increase in sand content. For mixes

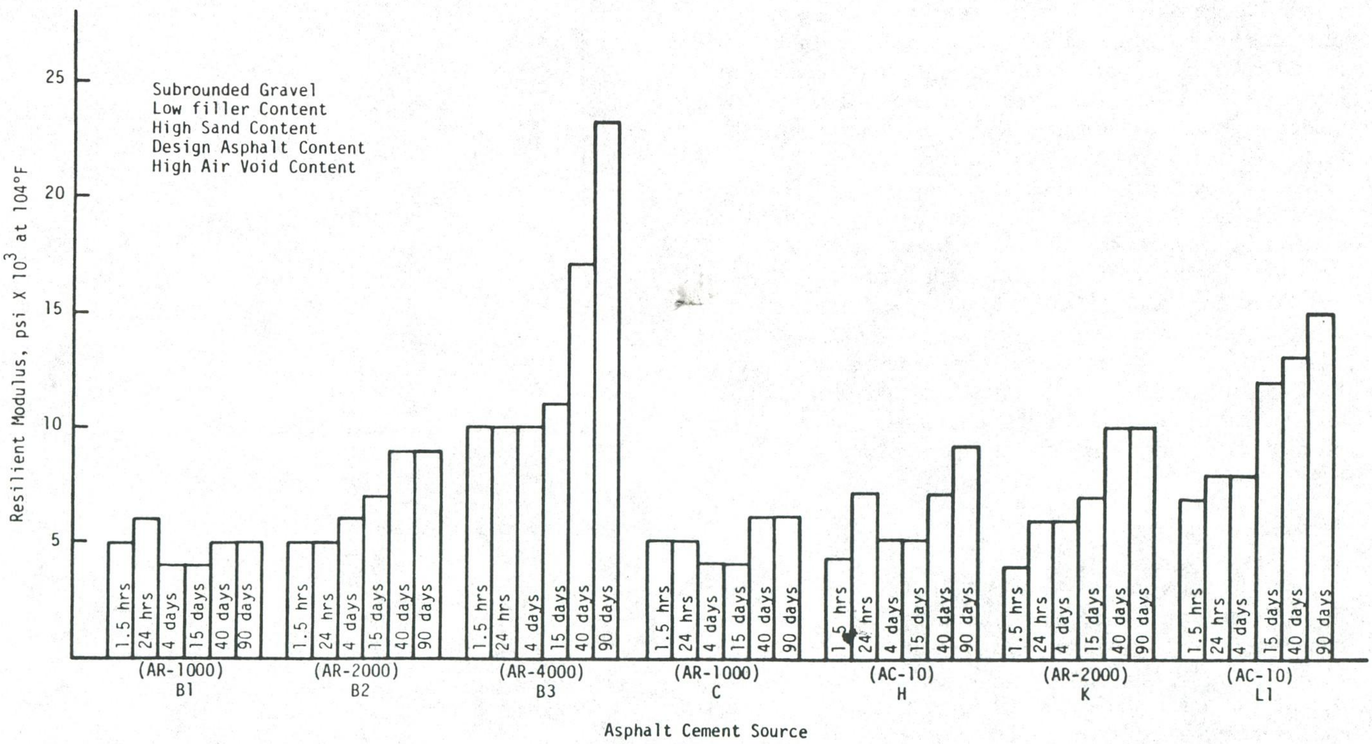


Figure 52. Change in resilient modulus with time—Test Plan b.

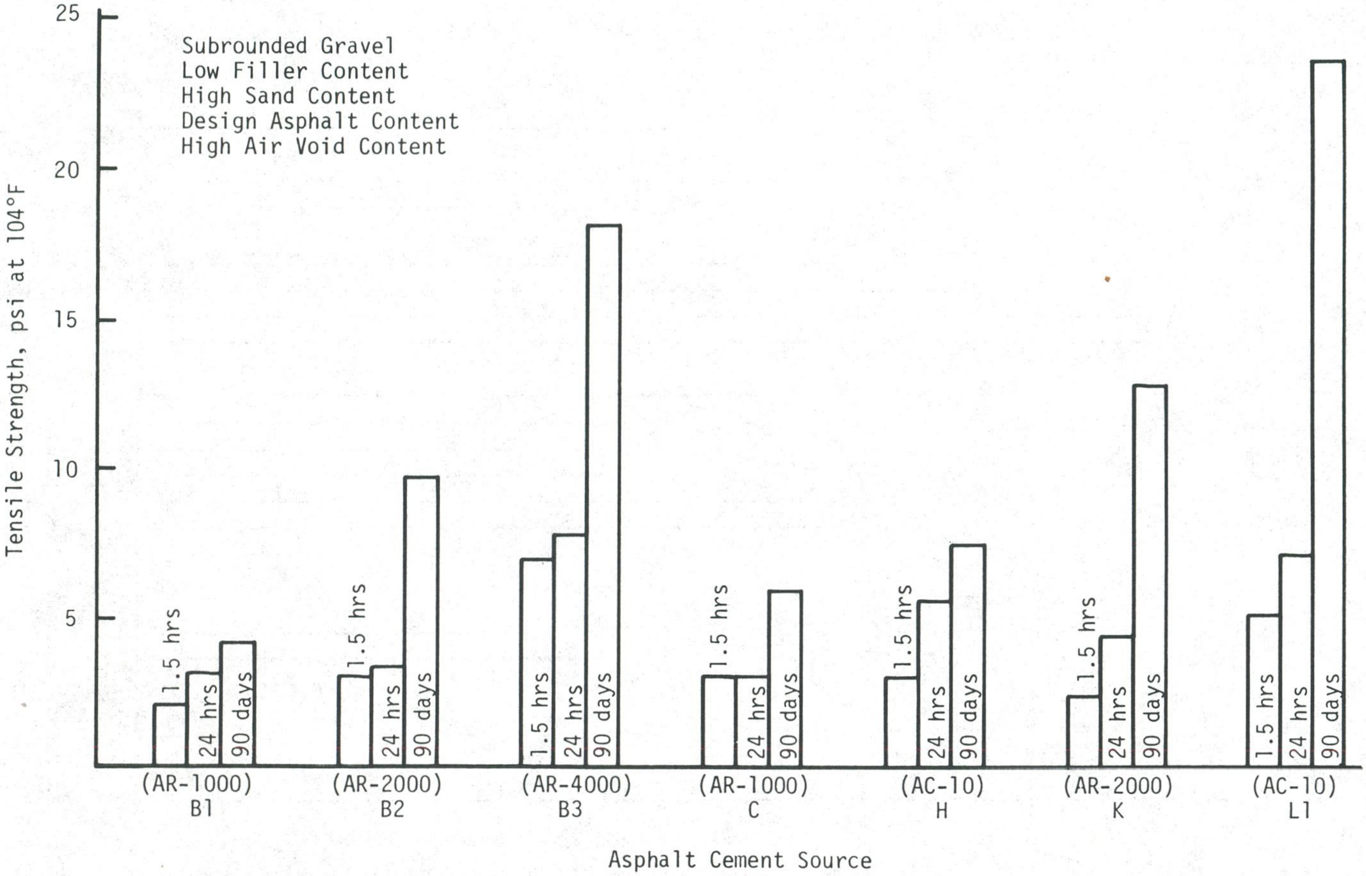


Figure 53. Change in tensile strength with time—Test Plan b.

with high filler contents, a decrease in tensile strength was noted with the addition of sand. A similar trend is evident for the limited data collected on mixes containing limestone aggregate. Mixture tenderness problems normally increase when sand contents are high. If the proposed 4 to 5 psi tensile strength criteria are valid, it is evident that the presence or absence of high sand contents does not change a mixture from tender to nontender or vice versa. It should be noted, however, that those mixtures with high sand contents generally required more asphalt. The additional asphalt in conjunction with the gyratory compaction process, which totally confines the HMAC in the mold, produced somewhat lower air voids. In the field, the compaction process does not completely confine the paving mixture and, therefore, aggregates with high sand contents will often resist compaction and yield high void contents.

All mixtures containing limestone aggregates (with the exception of one) have tensile strengths greater than the suggested 4 to 5 psi criteria. The mixture containing Asphalt K, low filler content, and low sand content has a tensile strength of 4 psi.

Asphalt Content

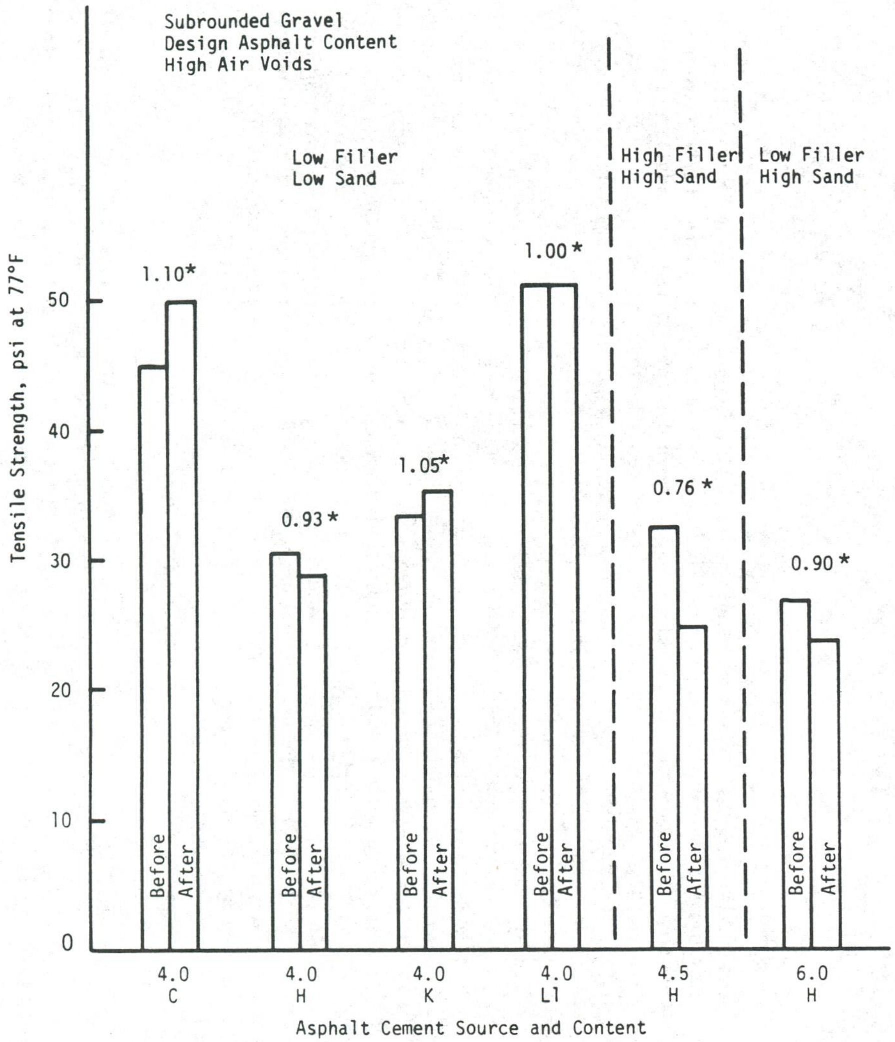
Asphalt contents referenced as optimum in this task were determined based on 50-blow Marshall mixture design procedures. Figures 57 and 58 show the relationship between tensile strength and asphalt content and resilient modulus and asphalt content, respectively. Optimum asphalt content for this combination of aggregates is 6.0 percent by dry weight of aggregate. Test results indicate that an optimum asphalt content exists for maximum tensile strength and resilient modulus. This result is supported by the literature.

The magnitude of the increase in tensile strength with changes in asphalt contents of the order of 0.5 percent is less than 2.5 psi and most often, less than 1 psi for the gravel aggregate mixtures. Thus, it is doubtful if small changes in asphalt content would significantly alter the rolling characteristics and early performance characteristics of most paving mixtures.

Limited tests were performed on mixtures containing limestone aggregates. Relatively large changes in tensile strength (4 psi) were noted with changes in asphalt content (Fig. L11).

Air Void Content

Figures 57 and 58 illustrate the influence of aid void content on tensile strength and resilient modulus. The observed trend of increases in tensile strength and resilient modulus with a decrease in air voids is supported by the literature.



*These values indicate ratios of tensile strength before and after moisture treatment.

Figure 54. Effect of asphalt source on water susceptibility—Test Plan c.

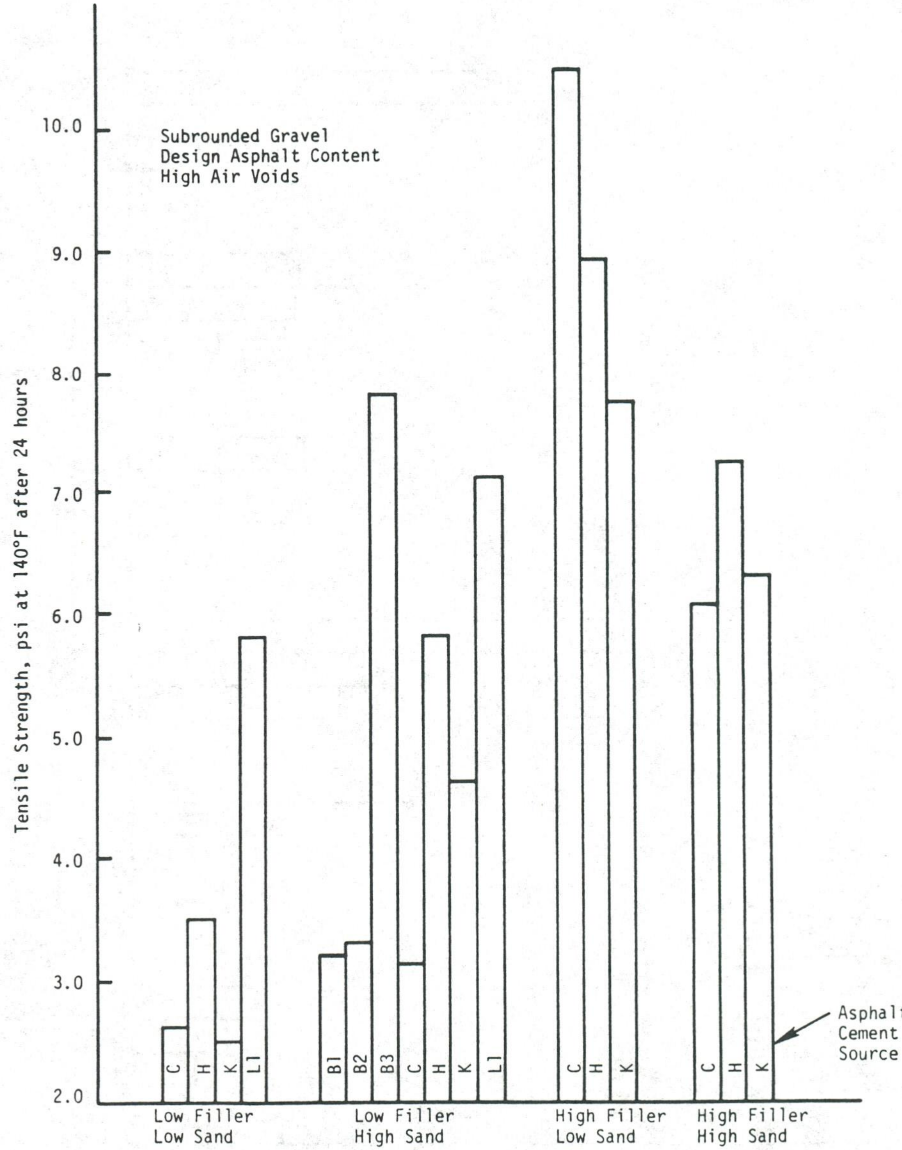


Figure 55. Effect of asphalt source on tensile strength—subrounded gravel—Test Plan a.

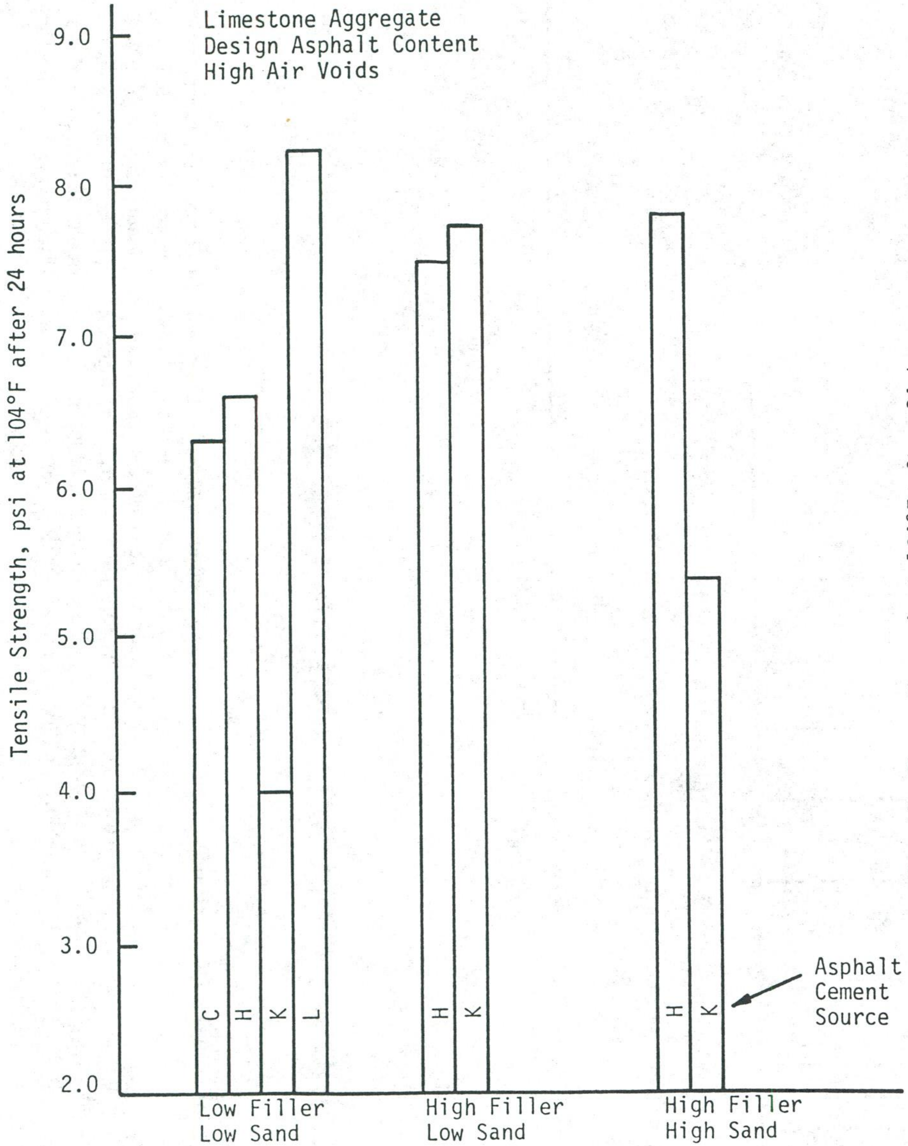


Figure 56. Effect of asphalt source on tensile strength—limestone aggregate—Test Plan a.

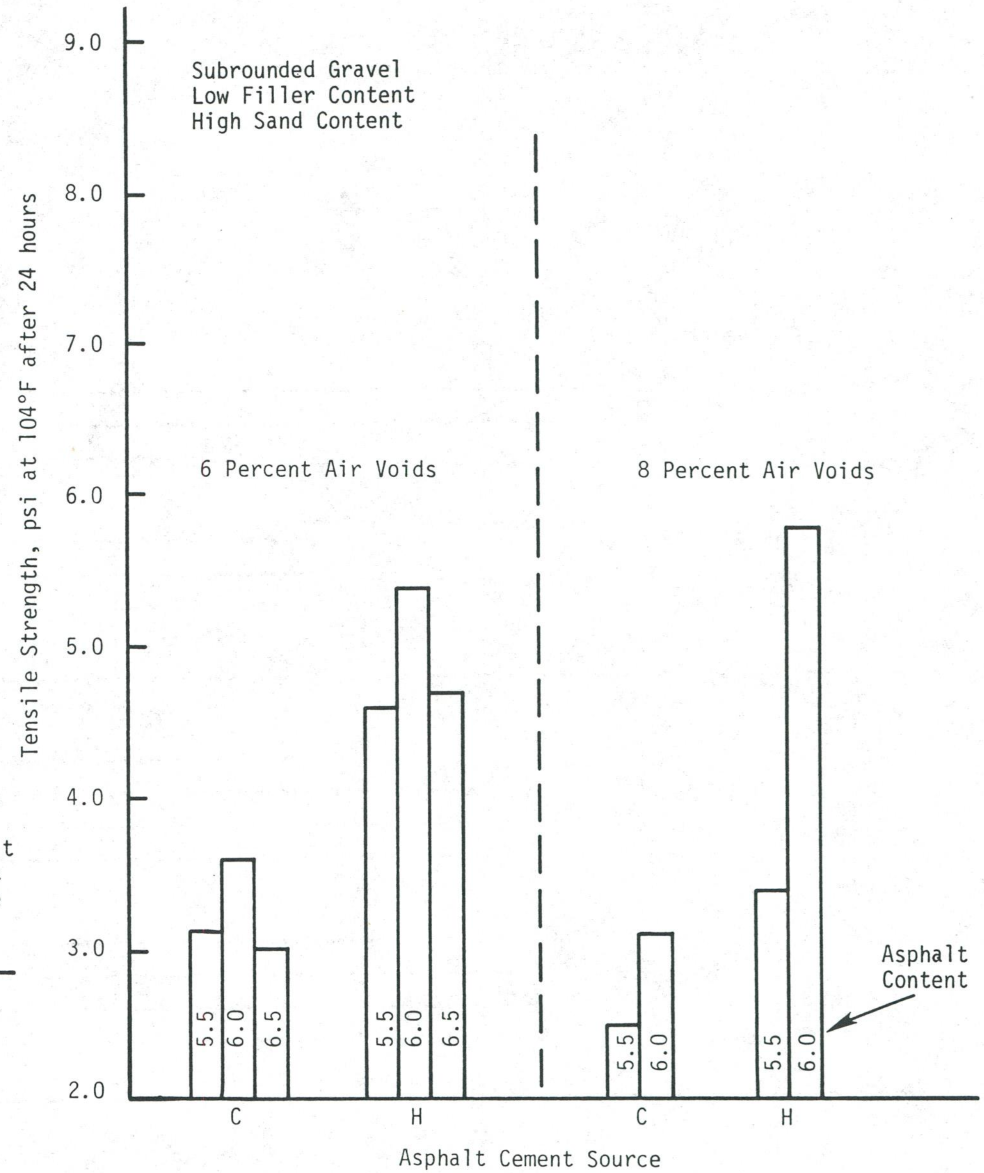


Figure 57. Effect of asphalt content on tensile strength—Test Plan a.

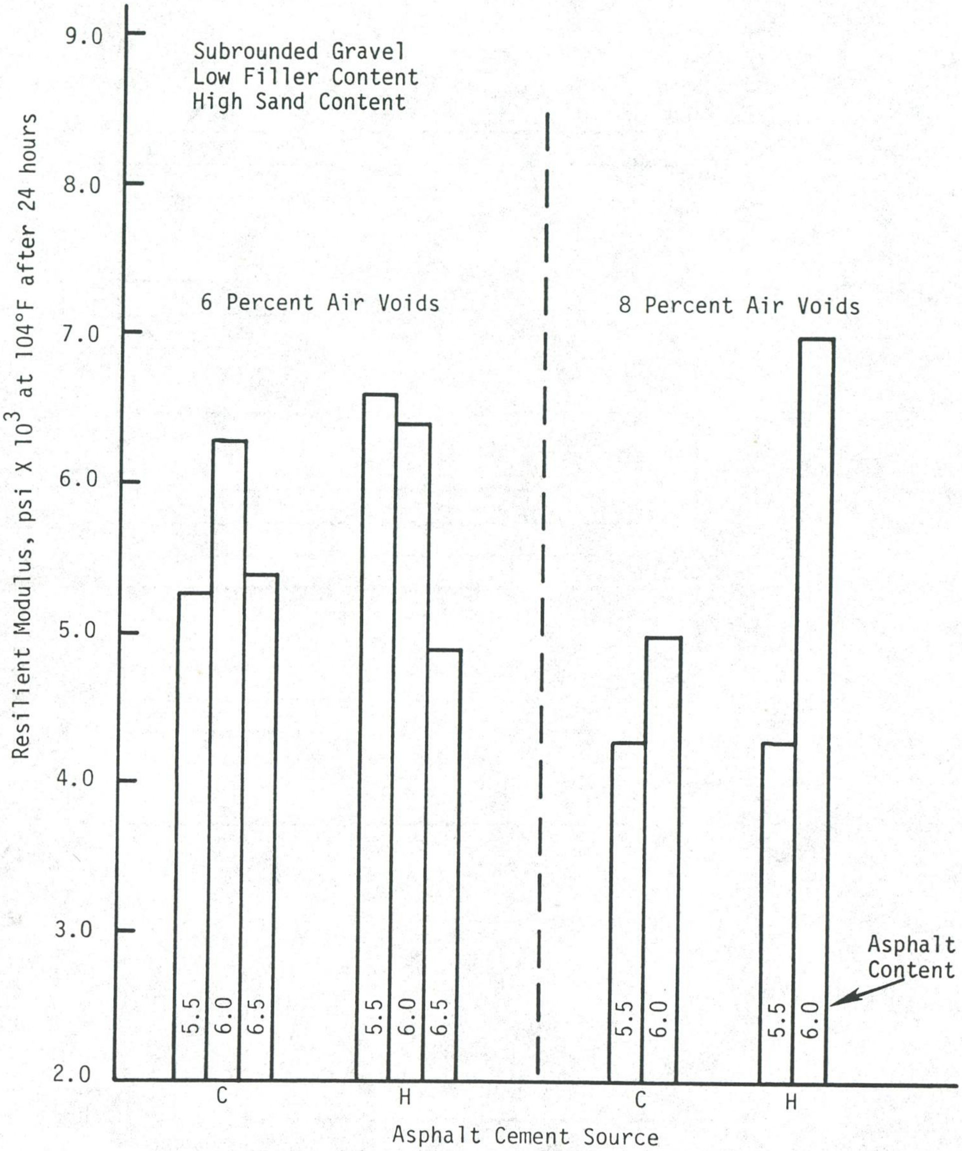


Figure 58. Effect of asphalt content on resilient modulus—Test Plan a.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

TEMPERATURE SUSCEPTIBILITY OF ASPHALT CEMENTS

Figures 1, 2, and 3 together with data presented on Table 1 indicate that the physical properties of asphalt cements produced today have the same range of values as those produced in 1960 and produced immediately prior to the 1965–1973 preembargo period. Statistical techniques have been used to indicate that mean values of particular asphalt cement physical-chemical properties varied over the years on a national and regional scale. Data collected from specific refining sources have indicated that the physical properties of asphalt cements from some refineries have changed with time, while asphalt from other refineries show no statistically significant change.

Overall, asphalt temperature susceptibility appears to have increased during the last 20 years. This increase in asphalt temperature susceptibility would, in all probability, not be noticed during conventional field construction operations and initial pavement performance periods. On the basis of the data collected and the construction operations observed during the course of this research project, a wide range of asphalt temperature susceptibility can be tolerated. In general, highly temperature-susceptible asphalts will cause construction difficulties only when aggregates of marginal quality are used. The problem will, of course, be aggravated by hot weather.

MIXING AND PLACING TEMPERATURES

Data published by The Asphalt Institute (*92*) indicate that mixing of the asphalt cement and aggregate should be performed at a temperature where the viscosity of the asphalt cement is 1.70 plus or minus 0.20 poises. Compaction should occur at a temperature when the viscosity of the asphalt cement is 2.80 plus or minus 0.30 poises. These criteria may be used to illustrate the effect of asphalt temperature susceptibility on mixing and placing temperature and thus provide an index to define the degree of change in temperature control that would be required to construct with different asphalt cements.

Figure 59 illustrates the maximum range of temperature susceptibility for asphalt cement that can be classified as AC-20 in the United States (Figs. 2 and 3). The differences between recommended mixing temperatures of these extreme asphalts is 40 F (22 C), while the difference between recommended placing temperatures is 34 F (19 C).

Figure 60 illustrates the maximum range of temperature susceptibility for asphalt cements marketed in northwest Texas. This difference is larger than that associated with the valley and coastal asphalts produced in California. The difference between recommended mixing temperatures of these asphalts is 40 F (22 C), while the difference between recommended placing temperatures is 34 F (19 C).

Figure 61 illustrates the maximum range of temperature susceptibility for a particular west coast asphalt for the period between November 19, 1974, and October 23, 1978. It is noted that the plotted data are after the RTFOT. Data presented on Figures 36 and 37 are original property data. The difference between mixing temperatures of these asphalts is 25 F (14 C), while the difference between placing temperatures is 22 F (12 C).

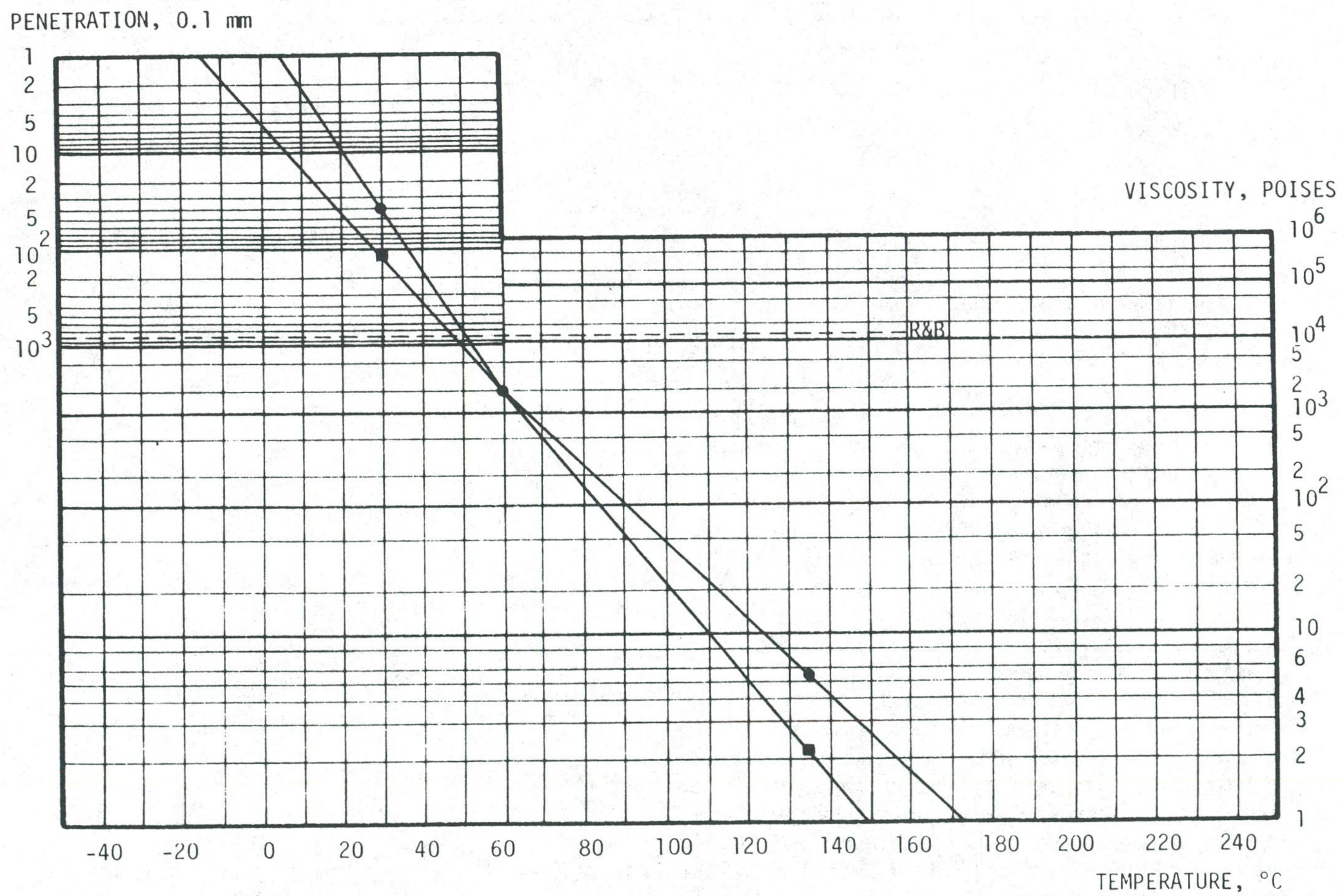


Figure 59. Range of AC-20 properties in the United States.

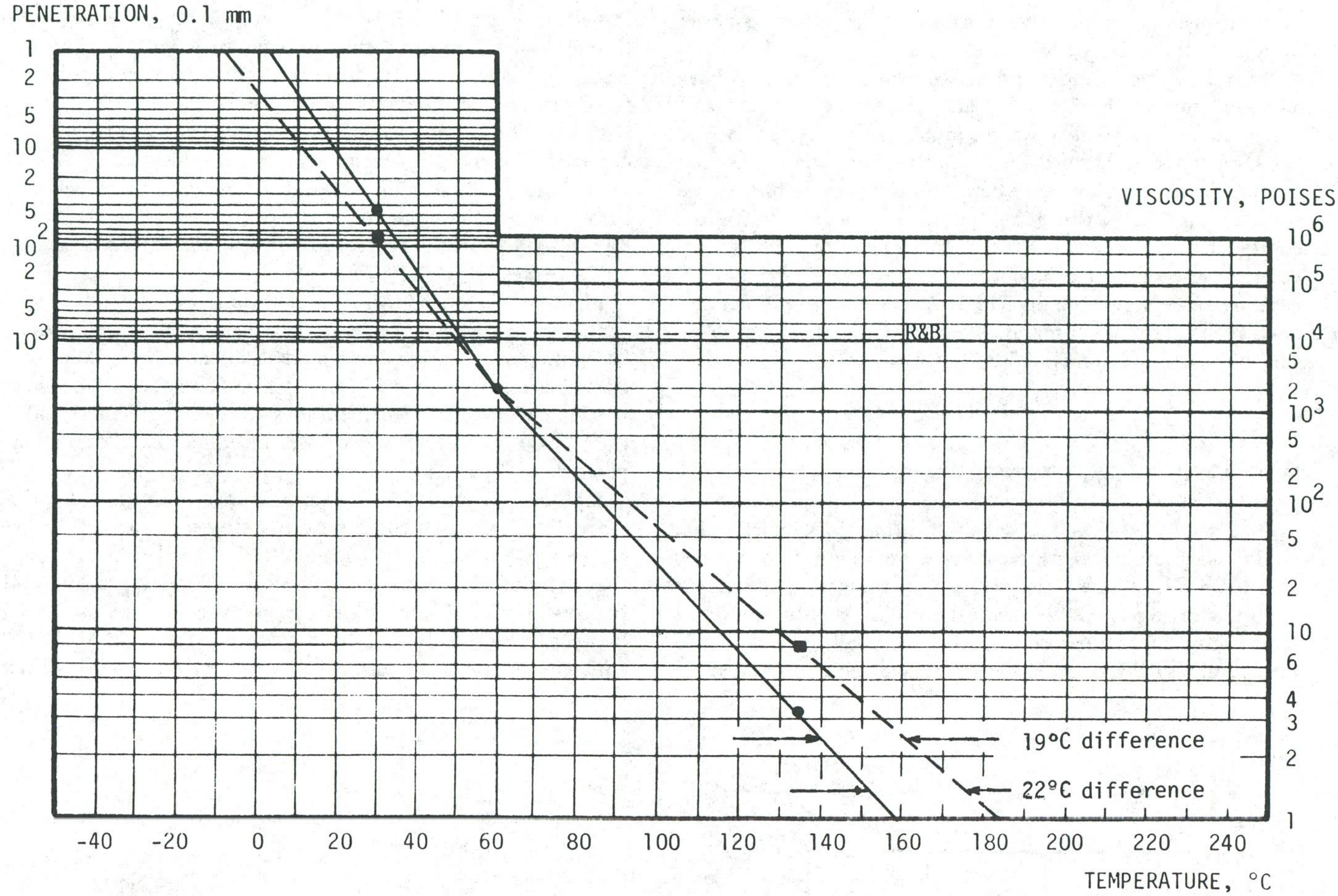


Figure 60. Range of AC-20 properties in a northwest Texas market area.

Figure 62 illustrates the maximum range of temperature susceptibility for a particular west coast asphalt for the period between April 10, 1977, to June 1, 1977. This is a period of time where a particular construction project would receive asphalt from this refinery. The difference between mixing temperature of these asphalts is 25 F (14 C), while the difference between placing temperatures is 22 F (12 C).

Occasionally, the incorrect grade of asphalt cement is delivered to a construction project and before the mistake has been recognized several truckloads of asphaltic concrete have been produced. Figure 63 illustrates the range of properties for an AC-5, AC-10, and AC-20 tested in this study (Asphalts A1, A2, and A3). The maximum difference in mixing and placing temperatures of those asphalts is 20 F (11 C).

Table 20 presents a summary of data obtained from Figures 59 and 60 and indicates that the contractor may have to adjust mixing and placing temperatures by as much as 35 to 40 F (19–22 C) to compensate for asphalt properties from a given market area. Asphalt cements from a given refinery source have changed sufficiently to possibly require the contractors to change plant temperatures 20 to 25 F (11–14 C) over a 2-month period. Asphalt cement grade changes from a given refinery (AC-5 to AC-20) will require plant temperatures to change from 15 to 25 F

Table 20. Differences in construction temperatures associated with asphalt temperature susceptibility.

Comparison Among	Temperature Difference (°F) For	
	Mixing	Placing
AC-20 Properties in U. S.	40	34
AC-20 Properties in Market Area	40	34
Production over 5-year period	25	22
Production over 2-month period	25	22
Asphalt Grade (AC-5 to AC-20)	20	20
Hot Mix Hardening	52	50

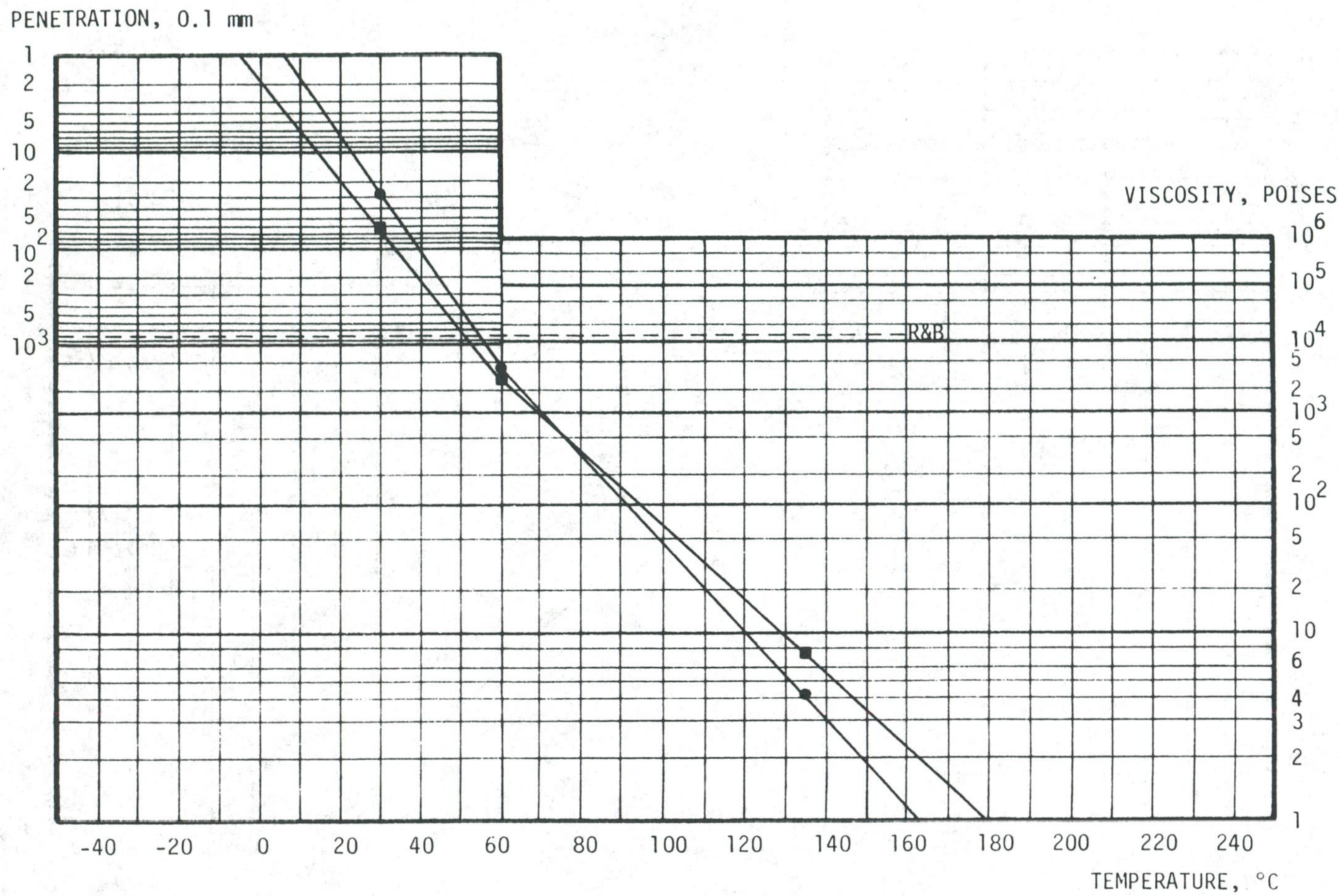


Figure 61. Range of asphalt properties after RTFOT for the period 1974–1979—west coast refinery.

(8–14 C). To put these temperatures differences into perspective, it should be pointed out that common specifications for hot mix production require a temperature range of plus or minus 25 F (14 C) around a given temperature target value.

LOW TEMPERATURE BEHAVIOR

The primary emphasis of this study was high temperature properties; however, some low temperature data have been collected. Highly temperature-susceptible asphalts (C and E) which have been associated with tender pavements were shown to have high viscosities in the low temperature range as compared to other asphalts tested in this study (App. E). Furthermore, the original asphalt properties (Table 9) indicate Asphalts C and E have the potential for low temperature cracking at a relatively high temperature. Asphalt C, which has good resistance to hardening, shows improved relative resistance to cracking after the TFOT. Results obtained after TFOT indicate that Asphalt E can be expected to crack at a relatively high temperature as compared to the other asphalts.

Figures 59 through 63 can be used as a crude relative measure of the asphalts' susceptibility to low temperature cracking. For example, if one assumes that low temperature cracking occurs when the penetration is 5, a relative temperature measure can be obtained. Figure 59 indicates that the temperature difference for low temperature cracking associated with AC-20 asphalt cements in the United States is 30 F (−1 C). Figures 60 through 63 can be used similarly and will indicate the following differences due to asphalt cement properties:

AC-20 property changes in Market Area (Fig. 60): 18 F (10 C)
Production over 5-year period (Fig. 61): 16 F (9 C)
Production over 2-month period (Fig. 62): 16 F (9 C)
Asphalt grade (Fig. 63): 34 F (19 C)

These temperature differences should be considered as significant in many parts of the United States.

ASPHALT HARDENING

A low level of hardening during the hot mixing process has been recognized as having the potential for contributing to pavement tenderness problems. Drum mix plants often do not harden the asphalt to the degree predicted by the TFOT and RTFOT tests. In addition, some asphalts have in recent years become

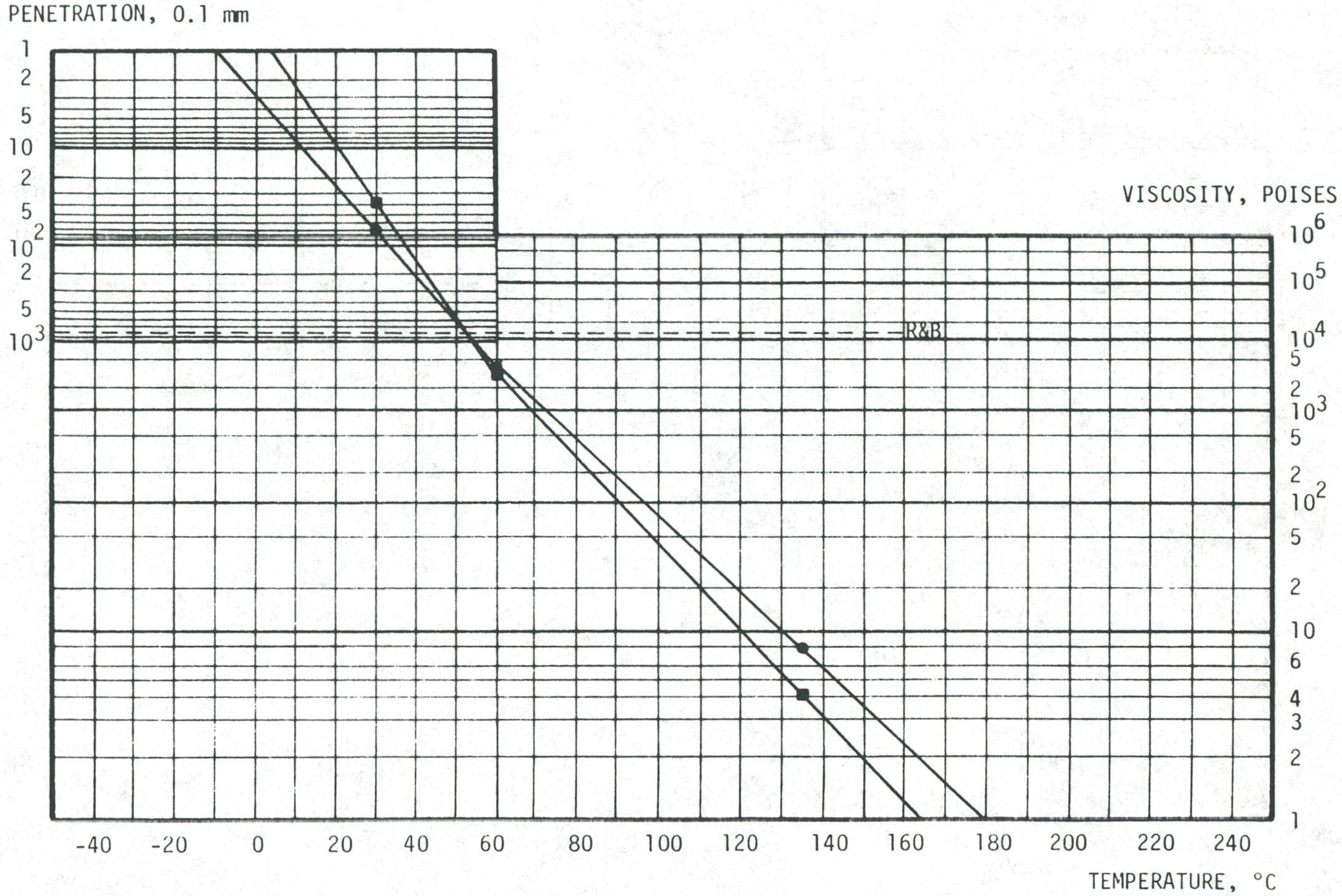


Figure 62. Range of asphalt properties after RTFOT for the period April 10, 1977 and June 1, 1977.

more resistant to hardening. Thus, softer asphalts often result after hot mixing and tenderness problems occur. Figure 64 and Figures B1 through B16 illustrate the magnitude of this potential problem for particular situations.

Figure 64 illustrates the maximum range of hardening experienced by AC-20 asphalt cements commonly used in the United States (see also Figs. 4, 5, and 7). If no hardening occurred as opposed to the hardening predicted by the TFOT test, the difference in compaction temperature would be 50 F (28 C). Figures B1 through B16 indicate that this compaction temperature difference for the asphalts tested is in the range of 5 F to 25 F (3 C to 14 C). A temperature difference of 25 F should be considered significant.

CHEMICAL PROPERTIES

Anderson and Dukatz (*55*) have indicated that both the Rostler and Gotolski parameters have increased over the time period investigated. The presence of high and low Rostler parameters and high Gotolski parameters in Anderson's 1979 data set indicates the presence of asphalt with potentially poor performance (*55*). These statements assume that the correlation between pavement performance and the calculated parameters are accurate.

Little asphalt chemical data have been presented which define changes with time from a given refinery. Historical data collected on asphalts from a southwestern state show some chemical property changes with time. However, the vast majority of the data show no significant changes (Table 7).

There is evidence to indicate that, as a general rule, asphalts with less than 10 percent asphaltenes (n-pentane insolubles), particularly the softer grades, will produce slow-setting mixtures. However, slow-setting mixtures will normally be manifested only when aggregate quality is marginal. These asphalts often exhibit good durability and excellent performance once they pass the initial setting period. Certain asphalts with high asphaltene contents may lack good durability. Depending on the situation, it may be possible to blend these types of asphalts to produce a superior paving material.

RECOGNITION OF TENDER MIXTURES

During the course of this research, it has become apparent that there are two distinctly different types of paving mixtures that are commonly referred to as "tender." One exhibits ten-

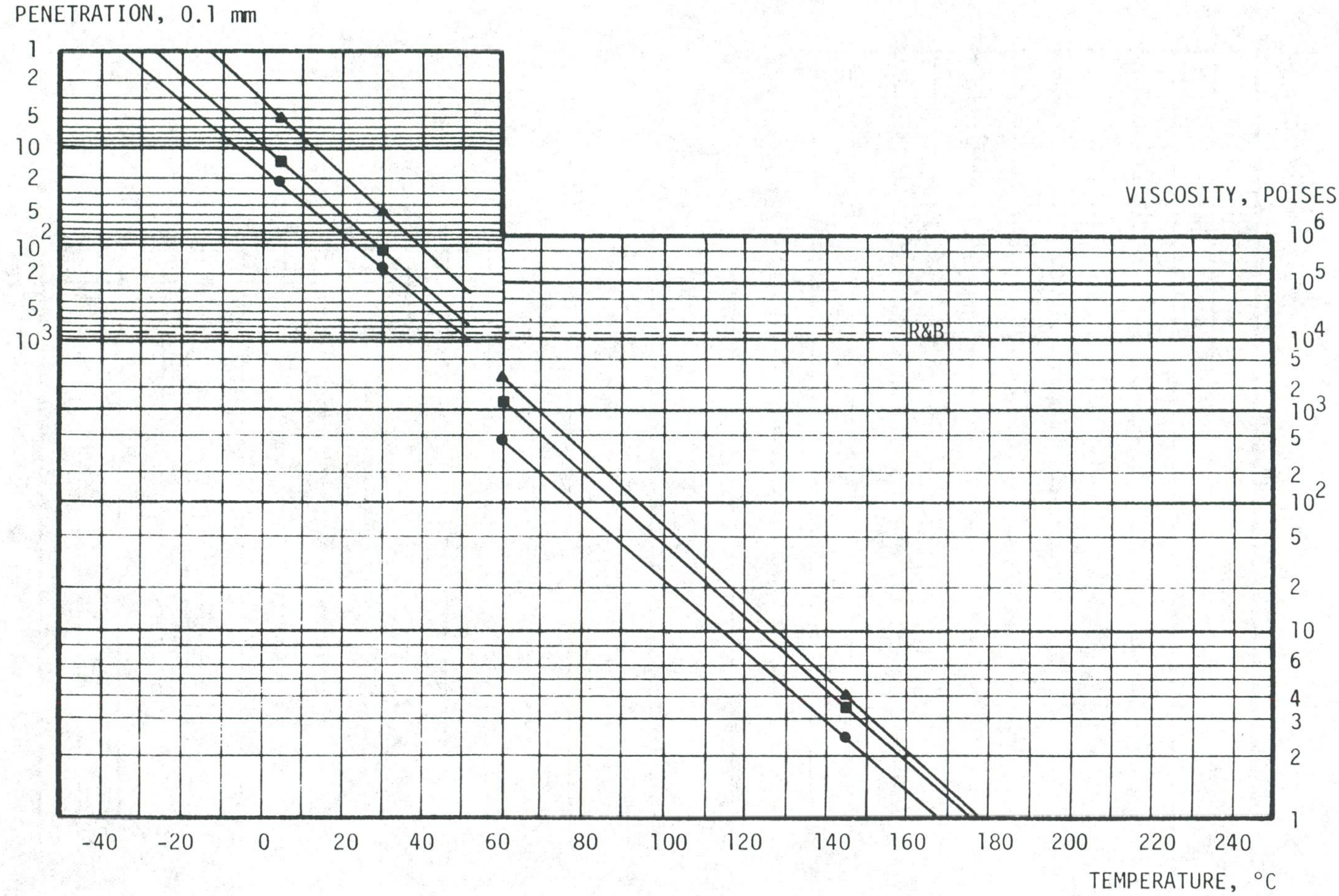


Figure 63. Range of asphalt properties for an AC-5, AC-10, and AC-20 produced in Texas.

derness *during* construction, which is characterized by being easily overstressed during compaction (i.e., shoving under steel wheel rollers or resisting compaction at normal temperatures). The other mixture is slow setting *after* construction, which is characterized by plastic instability or scuffing during the first few weeks after construction, particularly during periods of hot weather. Frequently, both of these characteristics will be exhibited by the same material.

Tenderness during construction is primarily an aggregate problem (caused by smooth, rounded aggregate, a high percentage of sand-size particles, and/or a low percentage of filler-size particles) which is aggravated by a highly temperature-susceptible asphalt. This mixture must be allowed to cool until the asphalt viscosity increases to a point where sufficient internal friction will prohibit overstressing by the steel wheels of the breakdown roller. Tenderness after construction is an asphalt-cement-related problem (caused by a slow-setting asphalt), which will manifest itself only if the aggregate type and/or gradation is such that a critical paving mixture is produced. The problem usually disappears within a few weeks.

Tenderness during construction appears to be related to asphalt temperature susceptibility; whereas, tenderness after construction appears to be related to chemical properties of the asphalt cement such as asphaltene content or degree of peptization. A slow-setting mixture will usually show some degree of tenderness during construction, but a mixture that is tender during construction is not necessarily slow setting. A slow-setting mixture is presently more difficult to accommodate than the mixture that is only tender during construction.

Ideally, the field engineer would like to recognize a mixture that will be difficult to compact and/or be slow setting, prior to placing in the field. Two possible approaches are proposed to assist the field engineer in the recognition of tender mixes prior to placement. The first approach uses the collective field experience of engineers to identify those material, mixture, and construction factors that contribute to tender mixes. The second approach uses laboratory tests and associated criteria for identification of mixtures that are likely to be tender during placement. These approaches are discussed as follows.

Material, Mixture, and Construction Factors

Table 21 contains a rating scale to identify the material, mixture, and construction factors that contribute to tender mixes. Important aggregate factors are (1) shape and surface texture of both the coarse and fine aggregate, (2) quantity of sand-size materials, (3) filler or minus No. 200 sieve fraction,

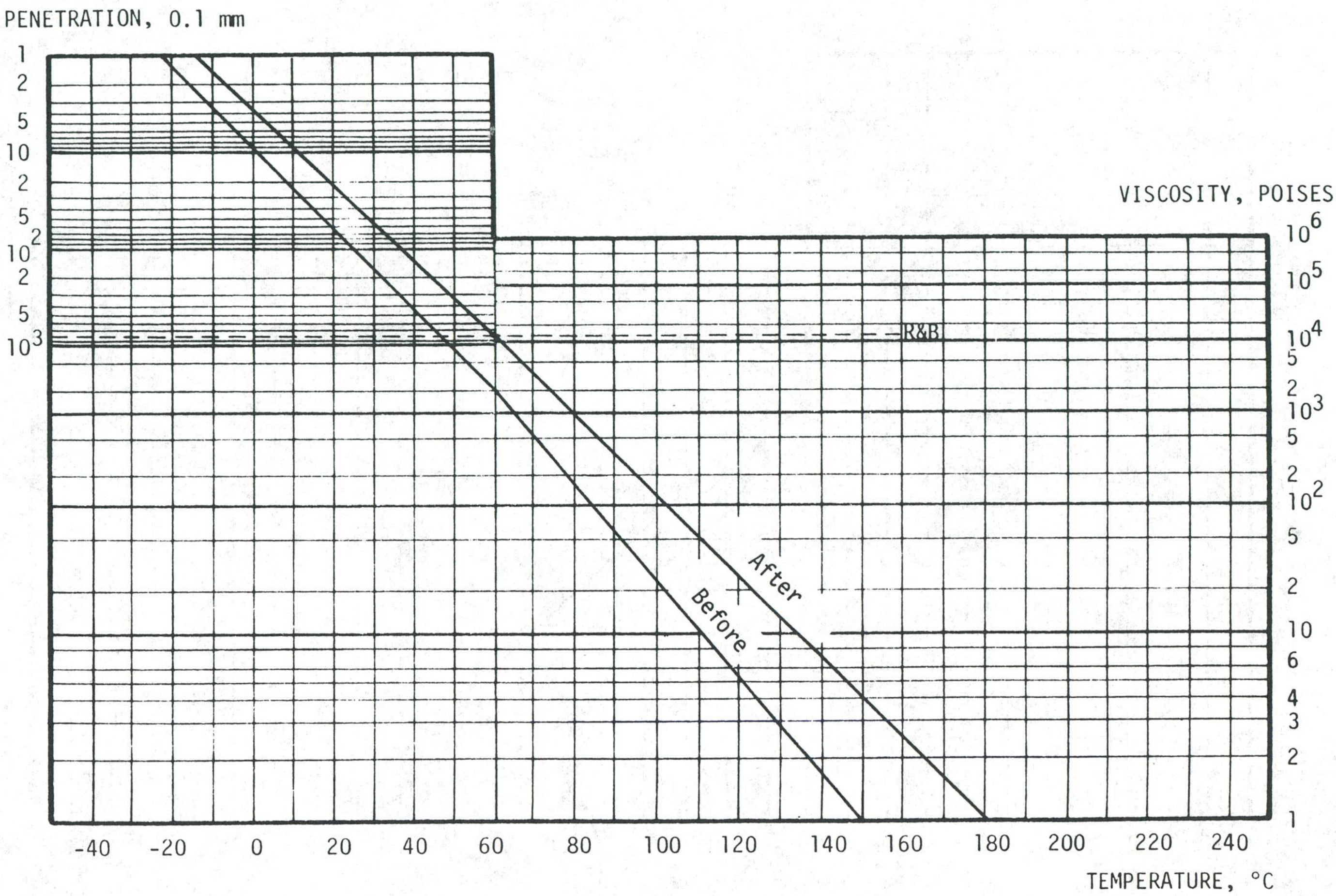


Figure 64. Range of AC-20 properties before-and-after TFOT.

Table 21. Rating scale to identify tender mixtures.

Material or Mixture Variable	INCREASING TENDERNESS → 1	2	3	4	5	6	7	8	9	10
Aggregate										
Shape	Angular		Subangular				Subrounded			Rounded
Texture	Very Round			Rough			Smooth			Polished
Maximum Size	>3/4-inch			<5/8-inch		<1/2-inch	<3/8-inch			<1/4-inch
-#30 to + #100*	Suitable					Excessive			Large Excess	
-#200	>6%		5%		4%		3%		<2%	
Asphalt Cement										
Content	Low					Optimum				High
Viscosity	High					Medium				Low
Penetration	Low					Medium				High
Hardening Index	High					Medium				Low
Temp. Susceptibility	Low					Medium				High
Setting Characteristic	Fast					Medium				Slow
Asphaltene Content	>20%					10 to 20%				<10%
Mixture										
Softening Additives	None					Some				Much
Moisture Content	<0.5%					1 to 2%				>2.5%
Construction										
Rolling Temperature	Low					Medium				High
C-value (88)	>50					30 - 50				<30
Ambient Temperature	<70		80				90			>100

*Suitable quantity depends upon design gradation. Rounded sand size particles can produce a critical mixture.

and (4) maximum size of aggregate in the mixture. Recognized asphalt properties of importance are (1) asphalt content, (2) asphalt consistency (penetration and/or viscosity), (3) temperature susceptibility, (4) hardening in thin film oven tests, (5) asphaltene content, (6) setting characteristics, and (7) use of asphalt additives such as liquid antistrip agents.

Construction operations also have an impact on the development of tender mixtures. Important factors are (1) mixing temperature, (2) compaction temperature, (3) amount of asphalt hardening during construction, (4) type of air quality control equipment, and (5) moisture content of mix during compaction.

As discussed previously, all these factors can influence the development of a tender mixture; however, some are more important than others. For example, mixtures that contain angular, rough surface textured aggregates in dense gradations and with proper filler contents rarely exhibit tenderness problems regardless of asphalt properties or construction operations. Mixtures containing subrounded aggregates with smooth surface textures, relatively high sand contents (gap-graded), and low filler contents will often be tender particularly when low viscosity asphalts are used. When the anticipated hot plant hardening of the asphalt is not achieved and when asphalts with low asphaltenes are used, the problem is amplified.

Ideally, a mathematical equation would be developed with the earlier listed material, mixture and construction variables. Each of these variables would be properly "weighted" to indicate its relative influence on tender mix development. A sufficiently large data base was not available to this project such that a reliable equation could be developed. A large and continuous research effort would be needed to develop such an equation. In the interim, the field engineer will have to assign the proper importance of each identified factor (Table 21) based on experience.

Laboratory Tests

This research project has investigated a number of laboratory tests to possibly identify tender mixtures. These tests include:

1. Resilient modulus of mixtures.
2. Indirect tensile strength of mixtures.
3. Marshall stability.
4. Hveem stability.
5. Asphalt temperature susceptibility (as defined by several parameters).
6. Asphalt consistency versus time relationship (viscosity and penetration).
7. Asphaltene content.
8. Asphaltene settling test.
9. Gel permeation chromatography (GPC).

Results from the testing programs performed on (1) selected asphalts, (2) mixtures obtained from field projects, and (3) laboratory-prepared mixtures indicate that the resilient modulus and indirect tensile tests performed on mixtures and the asphaltene content of the asphalt cement are the most meaningful tests for identifying potential tender mixtures in the laboratory.

Criteria for each of these tests as developed from project results are presented in Table 22. From the criteria of Table 21, it is suggested that the indirect tensile test and/or the resilient modulus test be performed on laboratory-mixed and laboratory-compacted specimens and the listed criteria be used.

Table 22. Criteria for tough and tender mixes.

Type of Samples Tested	Method of Test	Tough Mix	Tender Mix
Modified Compaction of Laboratory Mixtures (~8% air voids)	M_R* @ 104°F @ 24 hrs	>7,000 psi	<6,000 psi
	T.S.** @ 104°F @ 24 hrs	>5 psi	<5 psi
Modified Compaction of Field Mixtures (8-10% air voids)	M_R @ 104°F @ 24 hrs	>30,000 psi	<20,000 psi
	T.S. @ 104°F @ 24 hrs	>20 psi	<15 psi
Standard Gyratory Compaction of Remolded Field Cores	M_R @ 104°F @ 90 min	>130,000 psi	<125,000 psi
	T.S. @ 77°F @ 90 min	>165 psi	<140 psi

*M_R = Resilient Modulus

**T.S. = Tensile Strength

The criteria given in Table 21 have been developed for the following specific conditions:

1. Gyratory compaction (modified or standard).
2. Air void content at standard or higher values.
3. Test temperature of 104 or 77 F.
4. Loading rate of 2 in. per minute for indirect tensile test.
5. Load duration of 0.1 sec for resilient modulus test.
6. Sample age of 90 min or 24 hours.

If an agency does not have the equipment available to duplicate these conditions, a laboratory testing program should be initiated to define new criteria for their specific capabilities.

ASPHALT ADDITIVES

Pavement construction and short-term performance problems resulting from undesirable asphalt cement properties perhaps can be accommodated through the use of asphalt additives. Historically, such additives have been expensive. However, with the rapid cost increase of crude oil and asphalt cement, the cost of these additives is more reasonable from a relative cost standpoint. Thus, a number of new products have appeared and older products have reappeared on the market. Products which may improve asphalt cement temperature susceptibility and related construction and performance problems include sulfur (*93*), asphalt-rubber (*94*), Chemkrete (*95*), Asphadur (*96*), Accorex (*97*), Carbon black (*98*), selected other chemicals (*99*), blending of asphalts, synthetic fibers (*100*), and fillers. Field engineers are encouraged to use these additives in controlled field and laboratory experiments and report the handling, construction, and performance data for the general benefit of the industry.

CHAPTER FOUR

CONCLUSIONS

On the basis of the information presented in this report the following conclusions appear warranted:

1. Physical properties including temperature susceptibility of asphalt cements produced today have the same range of values as those produced in 1964 and those produced immediately prior to the 1965–1973 preembargo period (Figs. 1–7) (*54*). Statistical computations performed by Pennsylvania State University indicate that mean values of particular asphalt cement physical-chemical properties varied over the years on a national and regional scale (*55*). Data collected from specific refining sources in these studies have indicated that the physical properties of asphalt cements from selected refineries have changed with time, while asphalts from other refineries show no statistically significant changes (Tables 5–7 and App. A).

2. Limited asphalt cement chemical data exist which define changes with time from a given refinery (Tables 6 and 7). Results from the Pennsylvania State University study indicate that based on available chemical composition data, the number of potentially poor performing asphalts has increased by about 10 percentage points from 1964 to 1978 (*55*). This statement assumes that a reliable relationship exists among Rostler and Gotolski parameters and field performance.

3. Although some asphalt cement properties have changed significantly from a statistical standpoint, it is uncertain if these changes are significant from a pavement construction and pavement performance standpoint. Improved correlations between asphalt cement properties, asphaltic concrete properties, and construction and performance problems need to be developed before the significance can be reliably quantified. Limited analyses of information presented in the project indicate that changes in asphalt cement properties will affect construction if adjustments in field compaction temperatures are not made. For example, a contractor may have to adjust mixing and placing temperatures by as much as 35 to 40 F (19–22 C) to compensate for asphalt properties from a given market area. Asphalt cements from a given refinery source have changed sufficiently to possibly require the contractor to change plant temperatures 20 to 25 F (11–14 C) over a 2-month period. Asphalt cement grade changes from a given refinery (AC-5 to AC-20) will require plant temperatures to change from 15 to 25 F (8–14 C). Depending on the degree of hardening during hot mixing, compaction temperatures may have to be adjusted 25 F (14 C). As an alternative, a harder asphalt may be used.

4. Asphalt cements produced in the post-1976 period have a greater resistance to TFOT hardening and hence hot mix hardening than those asphalt cements produced prior to 1977 (Fig. 4). Asphalts tested in this study and obtained from 1979 and 1980 production have about the same range of basic properties (as measured before-and-after TFOT) as those asphalt cements produced in 1977 (Figs. 4 through 7).

5. Temperature susceptibility of asphalt cements is affected very little by the TFOT and RTFOT (Fig. 14 and Appendix D). Therefore, aging of asphalt cement in a hot mixing plant is not expected to significantly affect temperature susceptibility. The effect of TFOT and RTFOT aging on asphalt consistency is nearly identical over a temperature range from −40 to 275 F (−40 to 135 C) (Table 12 and App. E).

6. The correlation between asphalt cement properties and field tenderness was, for the most part, masked by variations in aggregate properties and/or construction techniques. However, highly temperature-susceptible asphalts and asphalt with high shear susceptibility have been associated with tender pavements. These same asphalts exhibit undesirable low-temperature characteristics that could lead to premature cracking.

7. Asphalts containing less than 10 percent asphaltenes, particularly the softer grades, appear to have a greater probability of producing slow-setting paving mixtures. However, an asphalt will manifest itself as slow setting only if the aggregate type and/or gradation is such that a critical paving mixture is produced (even though the aggregate may meet specifications) or possibly if densification of the pavement is inadequate.

8. The data indicate there is no correlation between asphalt temperature susceptibility and asphaltene content. There is no relationship between asphalt temperature susceptibility and other chemical constituents of asphalts as determined by the Rostler-Sternberg analysis or the Rostler parameter.

9. Asphalt consistency increases with time when asphalts are left undisturbed at 77 F; furthermore, on heating to 275 F the asphalt will return to its original consistency. Although this thixotropic property of asphalts is detectable using the standard penetration test or the sliding glass plate microviscometer at 77 F, it does not correlate well with setting rate in the field.

10. On the basis of the results of this study, asphalt properties alone will not cause a tender mixture during construction. If the aggregate quality is marginal such that a critical or tender paving mixture is produced, a highly temperature-susceptible asphalt can aggravate the problem at the higher compaction temperatures. When a high quality aggregate is employed, any asphalt meeting standard specifications can be used to produce a satisfactory paving mixture. High quality aggregate is largely angular, without an excess of sand-size particles, and is well graded with top size of 3/8-in. or greater and contains sufficient minus No. 200 sieve-size particles.

11. The indirect tensile test and the diametral resilient modulus test are more sensitive to asphalt consistency than the Marshall stability test. The Marshall stability test is more sensitive to asphalt viscosity than the Hveem stability test. Indirect tensile and resilient modulus tests at 104 F have the potential to identify tender and slow setting HMAC mixtures in the laboratory. Based on the guidelines developed in the course of this study, a specifying agency may develop criteria that can be used in the laboratory to avoid tender paving mixtures. In order to avoid tender mixtures, tensile strength of laboratory speci-

mens molded with approximately 8 percent air voids should exceed 4 to 5 psi when tested at 104 F at 24 hours after molding. In order to avoid tender mixtures, resilient modulus of laboratory specimens molded with approximately 8 percent air voids should exceed 6,000 psi when tested at 104 F at 24 hours molding.

12. Minus No. 200 mesh aggregate (and possibly other fillers) may be used in gravel-type asphalt paving mixtures to increase tensile strength and resilient modulus and thus would, in all probability, decrease mixture tenderness.

13. The mixture variables that have the greatest influence on resilient modulus and tensile strength of hot mixed asphaltic concrete are asphalt viscosity and filler content.

14. Since it is reported that the range in physical properties of asphalt cements is about the same now as in 1964 and immediately prior to the 1973 embargo, performance problems may be more related to quality control during construction. Emphasis should be placed on better training of design and construction personnel, improved inspection practices by highway departments, and, possibly, tighter materials and construction specifications (better compaction, angular aggregate, etc.). Quality control to minimize the probability of mixture tenderness should include: (1) high quality aggregate properties as listed in conclusion 10, (2) asphalt grade corresponding with the climatic region, (3) asphalt specifications addressing temperature susceptibility, (4) mixture temperature during compaction that is closely monitored, (5) and roller wheel diameter and weight that are appropriate to prevent overstressing of the paving mixture.

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