NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **269**

PAVING WITH ASPHALT CEMENTS PRODUCED IN THE 1980's

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **269**

PAVING WITH ASPHALT CEMENTS PRODUCED IN THE 1980's

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

AREAS OF INTEREST:

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

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.
DECEMBER 1983

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

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The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board, Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

By Staff
Transportation
Research Board

This report, NCHRP Report 269, and a companion report, NCHRP Report 268, "Influence of Asphalt Temperature Susceptibility on Pavement Construction and Performance," will be of special interest and value to individuals responsible for materials testing, mix designs, and construction of asphaltic concrete pavements. This 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. 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 the companion report. These findings indicate that the physical properties of asphalt cements are likely to be more variable today than they were 20 years ago, even though they remain within specification values; but, variations in other factors may mask the influence of this variation on pavement performance.

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 asphalt cement testing and characterization. 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, the use of most asphalt cements 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 Asphalt 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., N.W., Washington, D.C. 20418.

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Note: Appendixes A–L appear in a Supplement to NCHRP Report 268; *see Foreword for availability*

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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 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.

Technical guidance for the investigation was provided by the following consultants: J. O. Izatt, Houston, Texas; C. R. Foster, Washington, D.C.; and A. J. Hoiberg, Denver, Colorado. Laboratory testing was accomplished by Chris Cook, Sidney Greer and others.

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PAVING WITH ASPHALT CEMENTS PRODUCED IN THE 1980'S

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 269,* "Paving With Asphalt Cements Produced in the 1980's," and in a companion report, *NCHRP Report 268,* "Influence of Asphalt Temperature Susceptibility on Pavement Construction and Performance." 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 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 ⅜-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 mixture tenderness should include aggregate properties as listed in conclusion 10; asphalt grade should correspond with the climatic region; asphalt specifications should address temperature suscepti-

bility; 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 manual identifies the changes that have occurred in asphalt cements, aggregates, construction equipment and techniques, structural pavement design considerations, traffic, specifications and quality control, during the last 10 years, that can affect the construction and early performance of asphaltic concrete pavements. In addition, it provides engineering guidelines to assist the engineer and technologists in constructing acceptable asphaltic concrete pavements.

Readers who have a need for more detailed background information with respect to the findings are encouraged to reference the companion report, *NCHRP Report 268,* and a supplement to that document (published under separate cover; see Foreword for availability) which includes the following appendixes:

- 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

CHAPTER ONE

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 field 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 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 forces 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 (plastic instability), 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 asphalt concrete use (*5*). Furthermore, the claims are often vague in nature and are not supported by definitive physical or 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; asphalt quality, asphalt quantity, asphalt consistency, air void content of mixture, water susceptibility of mixtures, nature of 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 nations highways. Basic societal changes have placed ever changing performance demands on paving materials.

During the last 10 to 15 years pavements have been subjected to an increasing number of vehicles. Construction equipment has changed to improve production, air quality, workman safety, and material changes have occurred due to crude supply and transportation costs. These changes and their impact on construction and early pavement performance are discussed in Chapter Two. That chapter also identifies the changes that have occurred in materials, construction equipment and techniques, structural design of pavements, traffic, environment, and specifications and quality control. Information is provided in Chapter Three which guides the engineer in selecting the types of asphalt cement for a given project as well as in identifying sources of field construction and early performance problems.

CHAPTER TWO

CHANGES IN THE ASPHALT CONCRETE CONSTRUCTION INDUSTRY

ASPHALT CEMENTS

The recent field concern relative to the quality of asphalt cements has been largely responsible for the initiation of three major research efforts to define historic changes in asphalt cements (*1, 6, 7, 8*). These research projects were conducted at The Asphalt Institute, Pennsylvania State University, and Texas A&M University.

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 temperature susceptibility. Data obtained on the 1977 samples were compared with asphalt cement samples obtained and tested prior to the 1973 oil embargo. The pre-embargo 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 this study (*6*). They are 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 oil and the method of manufacture 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.

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 representing over 700 asphalts produced in 1950's, 1960's, 1977, 1979, and 1981. These data sets were those used in The Asphalt Institute study.

The FHWA fingerprint file was utilized to define physical-chemical properties of two data sets (*9*). The 1950 FHWA data set contained 311 asphalts, while the 1960 data set contained 58 asphalts. The 1950 asphalts were collected as part of a series of studies to define the characteristics and performance of penetration-graded asphalts (*10, 11, 12*). All of the asphalts included in the 1950 data set were commercially produced.

The asphalts in the 1960 FHWA data set were sampled as part of a cooperative program between the Asphalt Institute and the Federal Highway Administration to develop a viscosity grading specification (*13*). These are the same asphalts as those used in Puzinauskas's study reviewed previously and identified as having been produced in the 1960's.

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

The final data set representing post-embargo asphalts was collected by Pennsylvania State University in 1980-1981. Samples of asphalt cement, loose asphaltic concrete, and field core samples were obtained on over 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 or by the use of advanced statistical techniques. Conclusions presented by Pennsylvania State University researchers based on their analyses are given as follows (*8*):

> 1. Temperature susceptibility of asphalt cements in the low temperature region has increased over this time period 1950-1981.
> 2. When corrected for changes in hardness, the aging index or the increase in hardness on exposure to over 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 property that relates to a decrease in asphalt quality. However, this does not mean that such a decrease has not occurred; if it does indeed exist, currently available measurement techniques were not capable of detecting such a change.

Texas A&M University Study (1)

Texas A&M University researchers obtained data from 23 refineries in five states to define historic asphalt cement property variation by refinery source. Results of the study indicate that physical properties of asphalt cements from selected refineries have changed with time; whereas, asphalts from other refineries show no significant change. Physical property changes have occurred in an asphalt from a specific refinery which would require the optimum mixing and placing temperature to be altered 20 to 25 F over a 2-month period. These data are presented in Table 1 and Figure 1.

Historical chemical property data from asphalts from a given refinery are, in general, not available in the published literature. Table 2 is indicative of the type of limited data that are available and, thus, no conclusions should be made relative to a specific refinery source.

The Pennsylvania State University Study results indicate a trend toward an increase in the percent nitrogen base and a decrease in the first acidaffins during the time period 1950-1981. Other Rostler-Sternberg chemical components have remained relatively constant over the time period including the Rostler parameter associated with asphalt durability (*8*).

Discussion

The three studies referenced in the foregoing paragraphs indicate that, in general, the physical properties of asphalt cements produced today have the same range of values as those produced prior to the oil embargo. However, asphalts from specific refineries have exhibited historic changes in properties which the contractor must consider in the construction process. In addition, data have been presented by Pennsylvania State University which illustrate that the temperature susceptibility of asphalt cements in the low temperature region has increased over the time period 1950-1981. This trend has been confirmed by the Texas A&M University Study for specific refineries and also has noted a historic decrease in penetration at a number of refineries.

The reasons for these observed changes in asphalts by refinery source are complicated and will not be included here. However, some of the more fundamental causes are briefly discussed including crude source, refining techniques, and refinery economics.

Crude Source

Assuming the absence of additives, crude source and refining techniques determine the physical and chemical properties of asphalt cements. During the last 10 years refineries have been forced to use a larger than normal number of crude sources.

Table 1. Asphalt property changes for an AR-4000 produced in a western refinery. (Source: Ref. 1)

		Properties							
		Original	RTFOT Residue						
Refinery	Date	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

Figure 1. Range of asphalt properties after RTFOT for the period April 10, 1977 and June 1, 1977. (Source: Ref. 1)

Table 2. Chemical analysis of two California asphalts over the period 1960 to 1975.* (Source: Ref. 1)

Asphalt Designation	Year	Rostler-Sternberg						Rostler Parameter	$\frac{N}{P}$
		Asphaltene	Nitrogen Base	1st Acidaffins	2nd Acidaffins	Paraffins	Wax		
Valley	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	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.

This has resulted from uncertainties associated with supplies from foreign governments, depletion of old crude oil fields, development of new oil fields, effects of price decontrol of crude oil, and pricing structure of crude oil supplies.

At some refineries these changes in crude oil supply have created short-term uniformity problems relative to the properties of the asphalt cement produced. Although blending of crudes prior to refining has long been practiced by the industry to achieve uniform product streams, more blending of crudes is often required today to produce desired end products. Of the 78 refineries sampled in the 1977 Asphalt Institute study only four were using unblended crudes (*6*). Most asphalt cements are refined from blends of crude oil from at least two sources and some from as many as four sources. Blends of domestic and foreign crude oils are frequently used. It should be pointed out that crude oils collected from different wells or strata in a given oil field or crude basin are blended before processing.

Approximately 1,450 crude oil streams exist in the free world. About 975 of these crude streams are presently being used in the United States. Approximately 190 of the 975 crude streams found in the United States are suitable for manufacturing paving asphalts. For a given region of the United States (i.e., East Coast, West Coast, Gulf Coast, Mid-Continent, Rocky Mountain areas) a maximum of only 41 crude streams are economically available. The number of crudes used today in U.S. refineries is only slightly higher than the number used 5, 10, and 15 years ago (*14*).

Refining Techniques

Atmospheric distillation, distillation at reduced pressure, air blowing, and solvent refining are the major methods used for the production of asphalts. These basic processes have not changed for a number of years, and The Asphalt Institute study states that "based on the available information, it is clear that the manufacturing processes or methods used today are identical or similar to those used to produce asphalt before the oil embargo" (*6*).

Distillation remains by far the most common process. Steam and a vacuum are often used to lower processing temperature in order to reduce undesirable thermal conversion which may adversely affect the properties of the asphalt (*6*). Solvent refining processes have been used at several midwest refineries for a number of years. Since 1979 seven "new process' solvent refineries have been constructed. The new ROSE (*R*esiduum *O*il *S*upercritical *E*xtraction) process has been developed for upgrading heavy crudes and residuals. The process is capable of producing asphaltenes, resins, and deasphalted oils. Asphalts are currently being produced from this new refining technique. Detailed property data and field performance studies have not been published to date (*15, 16*).

Any of the major processes identified above may be used to manufacture asphalts to any given grade. However, a common practice involves processing materials to low and high grades and then blending to intermediate grades. Fluxing of harder grades of asphalts to meet intermediate and soft grades is practiced more commonly in today's refineries than in the past.

Refinery Economics

Historically, profits within oil companies have been derived from sales of light fuels and petrochemical feedstocks. In the early years, products from the bottom of the barrel, such as asphalt, were often difficult to dispose of at a profit. Hence, refineries developed processes to alter those high molecular weight materials for use as fuels or petrochemical feedstocks. The ROSE process is such a process; it attempts to utilize a larger portion of the bottom of the barrel for products other than asphalts and heavy fuels. Figure 2 shows a simplified representation of available refinery options.

Depending on the nature of the crude, the refining process, and the product demand, the quantities of heavy fuel oils and asphalt produced can be varied. Late summer, fall, and early

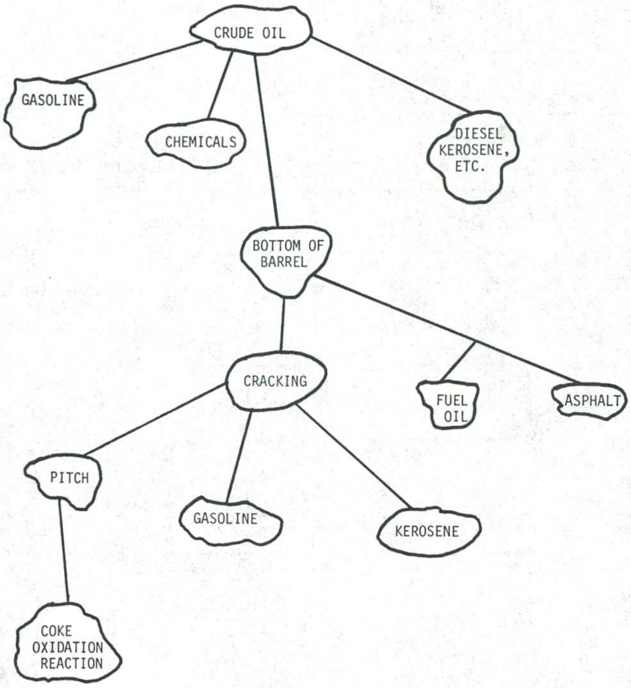

Figure 2. Refinery options.

winter refining operations in some areas of the United States will produce relatively large quantities of heavy fuel oils, while late winter, spring, and summer production will be relatively large quantities of asphalt. This production variation satisfies the seasonal demand for products while limiting costly storage.

Cracking units have recently been installed at some refineries and specialty companies have been formed which are equipped with cracking units to further refine the bottom of the barrel. Economics have dictated these installations as increased quantities of heavy crude oils are required to be refined. These increased quantities of heavy crudes result from secondary and tertiary crude oil recovery techniques, production from new fields with heavier crudes, and foreign purchasing requirements in which both "light" and "heavy" crudes must be purchased.

Since heavy crudes produce increased quantities of heavy fuels and asphalts as low profit margins, refineries are more seriously considering the installation of cracking units or the newer solvent extraction processes. When cracking units are installed it is likely that a significant portion of the bottom of the barrel at the refinery will be diverted to cracking unit. Hence, reduced quantities of asphalt cement are likely to be available. Initial high costs and the presence of relatively high concentration of trace elements in the feedstocks for cracking units have limited installation in the last 5 to 10 years, and it is not likely that this chemical aspect will change significantly anytime soon.

A significant portion of the cost of refined end products is crude oil acquisition costs. Thus, oil companies are constantly "shopping" for relatively low cost crudes. This practice can lead to a refinery using a relatively large number of crudes in a relatively short period of time. As a consequence, physical and chemical properties of end-products could change significantly.

Industry research and development trends forced by market and cost considerations have recently indicated a reduced interest in asphalt production by the oil companies. This, coupled with the increased alternative use of the "bottom of the barrel" (for products other than asphalt), suggests that the paving industry should learn how to use asphalts as they are being produced today and as they may change in the future, and/or be willing to pay a price that will make asphalt as much of a profit item as many other products produced from crude oil.

AGGREGATES

Major sources of aggregates in the United States have remained essentially unchanged over the last 10 to 15 years. Local aggregate supplies have chaged in some cases because of large increases in transportation costs. From available published literature it is difficult to determine if changes in aggregate type and gradation have had a significant effect on performance. It is, however, evident that existing mixture design methods, which include weight-volume relationships and aggregate gradation considerations, should be revised to ensure adequate performance under heavy traffic (more repetitions of loads, higher loads, and higher tire pressures).

CONSTRUCTION EQUIPMENT

Major equipment changes that have occurred in the last 10 to 15 years include the widespread use of drum mixers, vibratory compactors, and the use of dust collectors. The use of drum mixers has also provided an economical opportunity for higher production capacities on a large number of jobs.

Drum Mixers

The effect of mixture temperature on asphalt handling during hot mixing is well established, as is illustrated in Figure 3 (*17*). Since drum mixers usually operate at lower temperatures than batch mixers, less plant hardening of asphalt is sometimes apparent. Figures 4 and 5 confirm this observation (*18*). However,

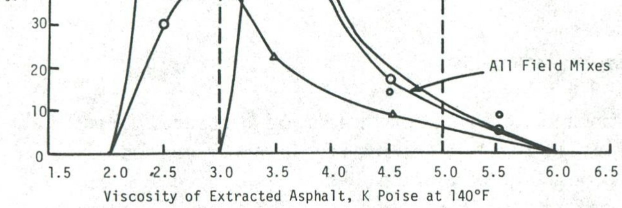

Figure 3. Effect of plant mixing temperature on asphalt viscosity. (Source: Ref. 17)

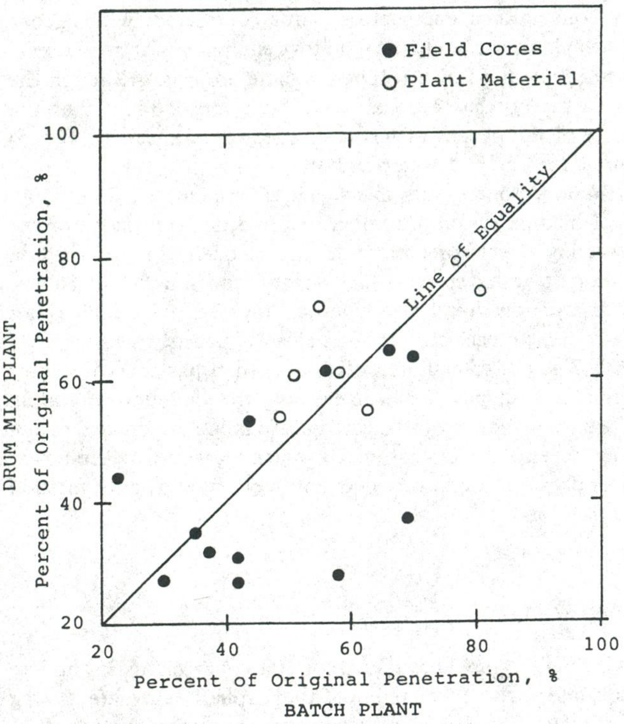

Figure 4. Comparisons of asphalt penetration for materials produced by different mixing processes. (Source: Ref. 18)

drum mixers have, on occasion, hardened asphalts excessively. As much as 20-fold hardening has occurred in some drum mixers (*19*).

Contamination of the asphalt with unburned fuel has also occurred in drum mixers. Both Oregon and California have experienced problems which resulted in an asphalt with a higher penetration after mixing as compared to before mixing (*18*). Figure 6 illustrates the effect of fuel type on the hardening of asphalt through drum mix plants.

Performance problems can result from excessively hardening the asphalt or from the asphalts not hardening to the degree anticipated. Proper maintenance and operating procedures will solve the excessively hardened asphalt problem. Recognition of the fact that drum mixers often will not harden the asphalt to the degree anticipated will allow the engineer to select a harder grade of asphalt if required for the project.

The Pacific Coast Paving Asphalt Specifications (ASTM D3381, Table 3) is based on asphalt properties after the material has been subjected to the rolling thin film oven test. This test adequately simulates hot mix hardening in batch plants when temperatures above 300 F are used, but does not reliably characterize the hardening in drum mix plants or batch plants operated below 300 F. Thus improper grade selection may result.

Vibratory Compactors

The use of vibratory rollers became popular during the 1970's. Because of their size and operational characteristics, these compactors are capable of achieving desired densities in fewer passes

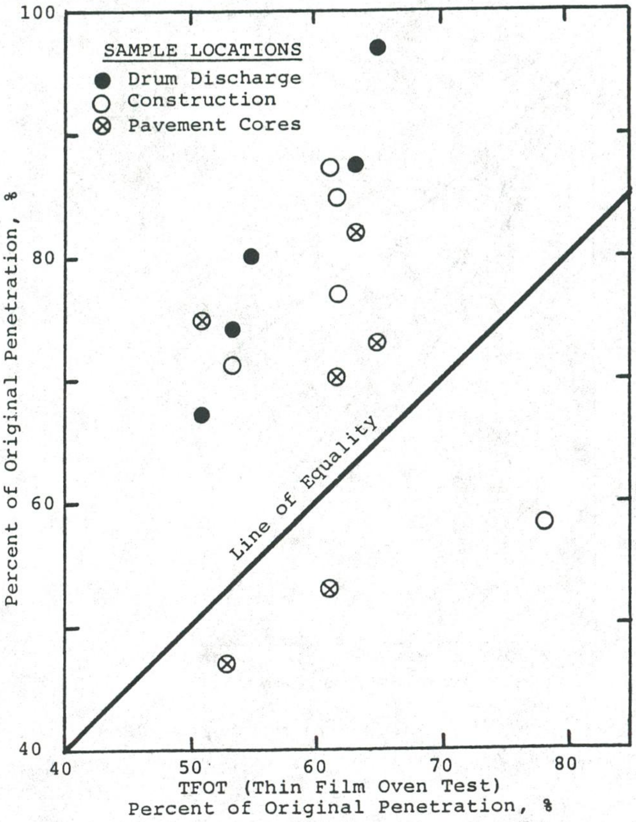

Figure 5. Retained penetration of asphalt mixtures at various points in the drum mixing process as compared to the TFOT. (Source: Ref. 18)

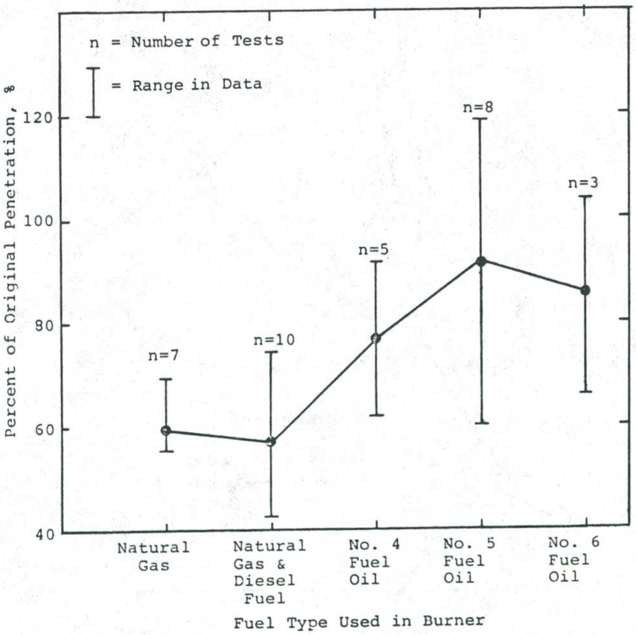

Figure 6. Effect of fuel type on the hardening of the asphalt through drum mix plants. (Source: Ref. 18)

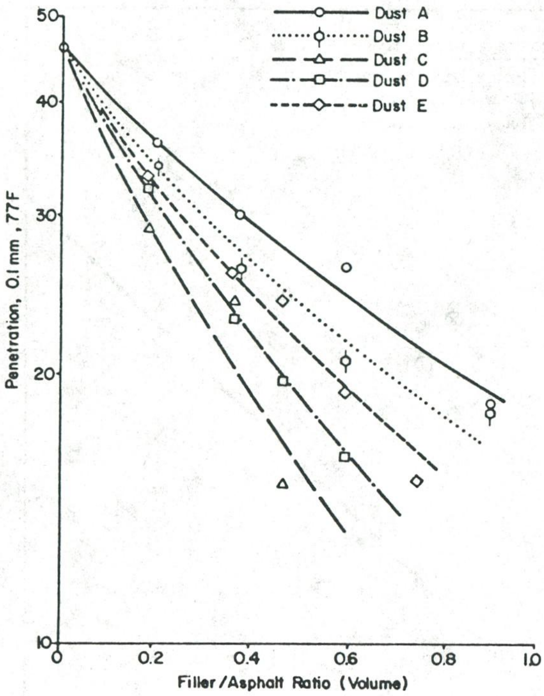

Figure 7. Effect of dust concentration on penetration at 77 F. (Source: Ref. 20)

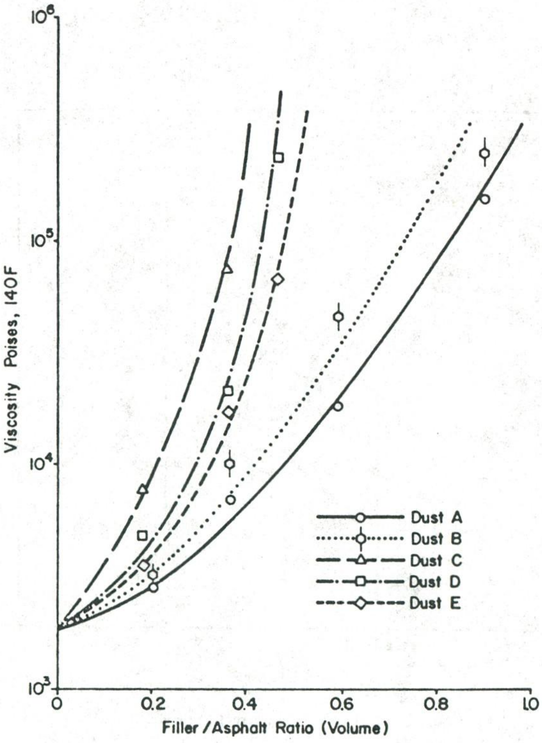

Figure 8. Effect of dust concentration on absolute viscosity at 140 F. (Source: Ref. 20)

than conventional compactors. Thus contractors with agency approval have used only the vibratory equipment for breakdown, intermediate and finish rolling on some projects. Although the desired density has been achieved, it is not evident that the surface of the pavement has been adequately kneaded (closed) to limit the entry of water and air.

Vibratory rollers, like most new equipment, have been operated incorrectly on a number of projects. Knowledge of the interacting effects of amplitude and frequency is required in addition to roller speed, roller weight, and number of passes. The use of low frequency vibration together with high roller speeds has, on occasion, created closely spaced waves in pavements. The use of high amplitude vibration has caused decompaction of thin pavements. Reversing the direction of rolling while in the vibratory rather than static mode has created rough riding pavements. Operational problems can be overcome by proper operator training and/or enforcement of detailed method specifications.

Baghouse Fines

Air quality guidelines issued for stationary plants in the late 1960's and early 1970's required that asphalt-aggregate mixing plants install baghouses or high energy wet washer systems. Wet systems precluded the entry of air-dispersed fines back into the mixing plants. In some cases, mixtures were produced that were short of filler and of low stability.

With the advent of the baghouse, it was possible to reintroduce the airborne fines into the mixture. Often the fines were not properly metered into the mixture and nonuniformity resulted. Studies performed by The Asphalt Institute and Anderson and Tarris (*20*) further define the problems by illustrating the effect of the type and amount of baghouse fines on penetration and viscosity of asphalts (Figs. 7 and 8).

Increased Capacity

High production rates are more common on today's construction projects as compared to projects 10 to 15 years ago. High production rates are possible because of improvements in mixing and handling capabilities and are necessary to reduce unit costs. Higher production, coupled with a reduction in inspectors, has resulted in less sampling and inspection. If the contractor does not provide his own quality control work force, more construction variability often results.

CONSTRUCTION TECHNIQUES

Use of proper construction techniques is often the most important factor that determines the overall performance of a project. Critical mixture preparation and construction steps are shown in Figure 9 and are listed as follows (*17*):

1. Asphalt transport.
2. Asphalt storage at hot mix plant.
3. Incorporation of additives into the asphalt.
4. Aggregate properties and filler content.
5. Mixing temperature.

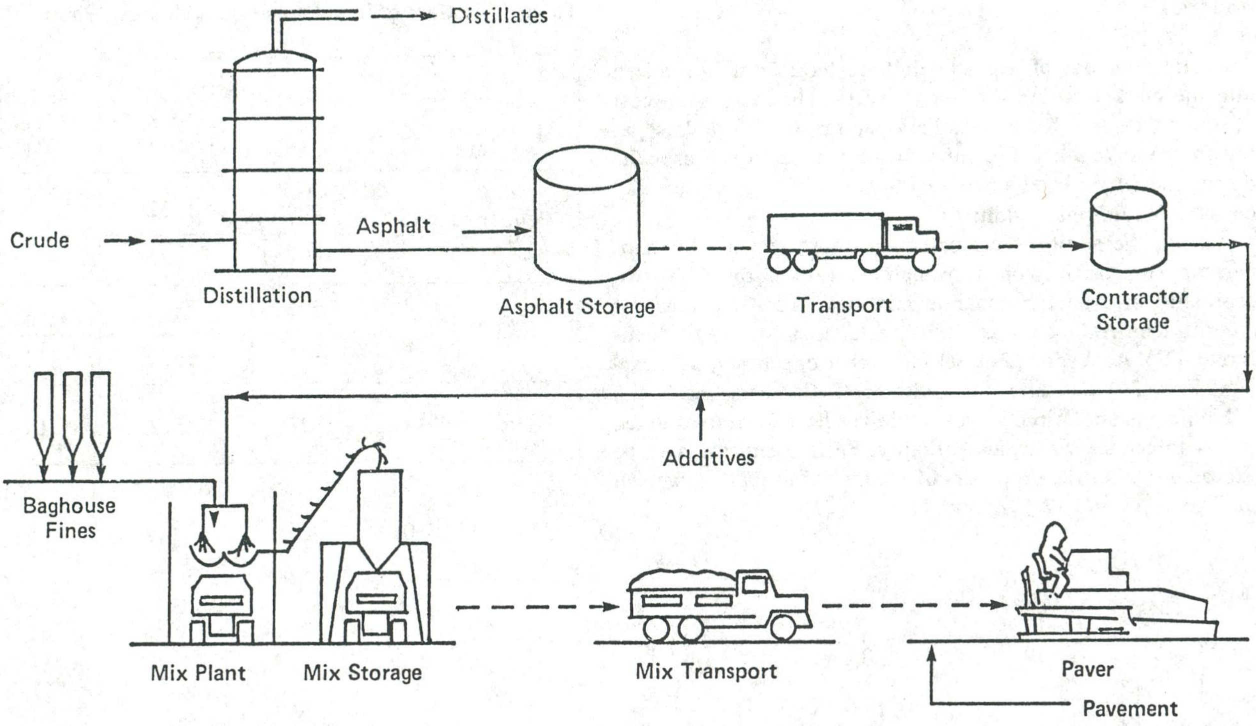

Figure 9. The paving process. (Source: Ref. 17)

6. Time of hot storage in surge bins and storage silos.
7. Placing operations.
8. Ambient and/or base temperature.

The effect of aggregate properties, filler content, and mixing temperature was briefly discussed earlier. Limited information is presented in the following discussion on the identified construction steps.

Asphalt Transport

During the last 10 years the average size of paving projects and the quantity of asphalt cement used in this country have decreased. Thus, fewer haulers are using dedicated vehicles for transporting asphalt. This practice increases the possibility of contamination from previously hauled products remaining in the truck, and it increases, as well, the chance of loading the wrong product into the truck. For example, a small quantity of cutback material or fuel oil (about 1 percent) can take an AC-20 out-of-grade.

Asphalt Storage at Hot Mix Plant

Problems occur when asphalts from more than one supplier are blended in the same storage tank at the plant site. As shown in Figure 10, two asphalts of the same grade can be mixed producing an asphalt out-of-grade because of chemical interaction (*21*). The practice of blending asphalts from different sources has become fairly common as contractors "shop" for low-priced asphalt in the present buyer's market.

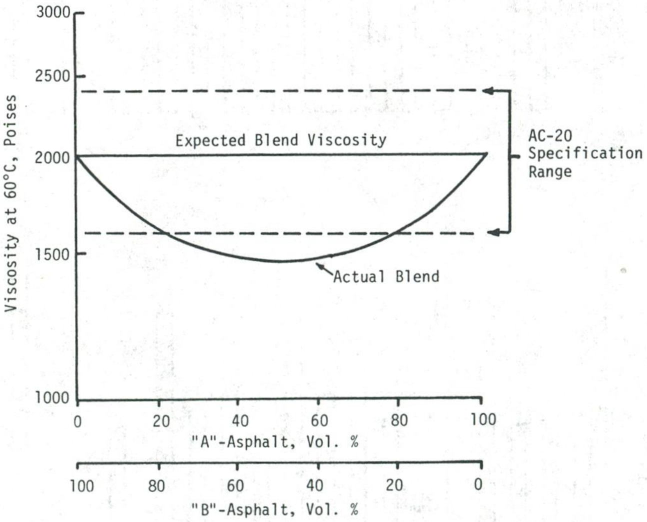

Figure 10. Effect of chemical interaction on blending of asphalts. (Source: Ref. 21)

During the recent rapid price escalation of asphalt cement several contractors purchased and stored large quantities of asphalt in pits excavated near their plants. Property changes of asphalts subjected to this type of storage environment have not been defined.

Additives

A large number of asphalt additives have been introduced into the market during the last 10 years. The increase in cost of asphalt cement from 30 dollars per ton to 175 dollars per ton in the 1970's and the concern for the quality of asphalts during the same period stimulated the interest of producers and consumers in asphalt additives.

Among the additives evaluated are those which alter temperature susceptibility of the asphalt cement and the water susceptibility of asphaltic concrete mixtures. Additives used for altering temperature susceptibility include; sulfur (*22*), Chem-Krete (*23*), Asphadur (*24*), selected other chemicals (*25*), carbon black (*26*), blending of asphalts, synthetic fibers, and fillers.

Numerous antistrip chemical additives have been used in asphalts to reduce water susceptibility. Such chemicals may be expected to alter the properties of the treated asphalts as shown in Figures 11 and 12 (*27*) and Table 3 (*21*).

Table 3. Effect of liquid adhesion additives. (Source: Ref. 21)

Test	Aging	Original Asphalt	Additive Treated Asphalt
Penetration, 77°F, dmm	None	62	79
	TFOT*	37	44
Viscosity, 140°F, poises	None	2250	1630
	TFOT	5570	3270
Weight Loss, percent	TFOT	0.117	0.42

*Thin Film Oven Test

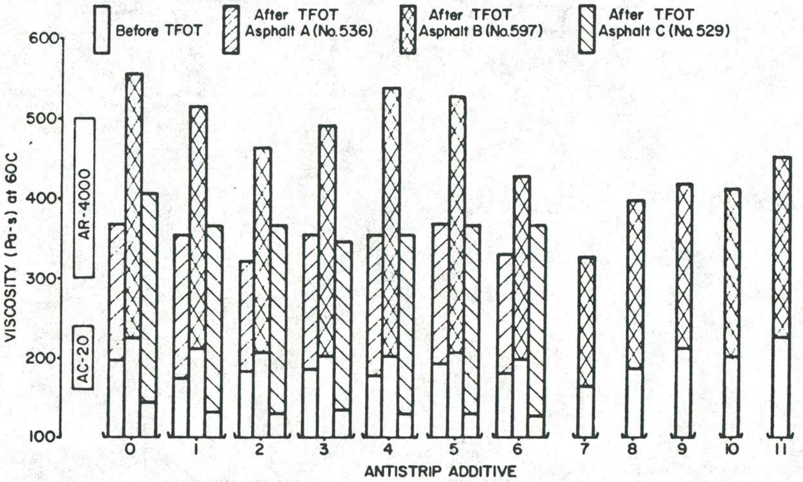

Figure 11. Viscosity at 60 C before and after TFOT. (Source: Ref. 27)

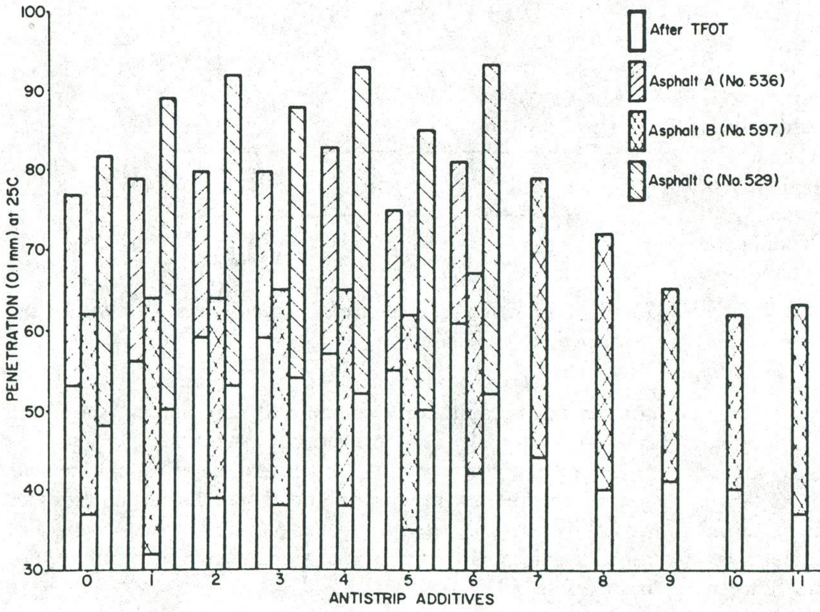

Figure 12. Penetration at 25 C before and after TFOT. (Source: Ref. 27)

Hot Storage

Asphalt viscosity can be expected to increase and penetration decrease when asphaltic concrete mixtures are stored hot (*28*). Storage of hot mix in a surge bin for 15 hours will increase the viscosity at 140 F from about 3,000 poises to over 8,000 poises. Fluctuating between short- and long-term storage can sufficiently affect asphalt properties such that changes in compaction operations are required. Durability of the final product is also affected.

Placing Operations

Among other factors, the compaction of asphalt mixtures is controlled by asphalt cement properties, aggregate properties, mixture temperature, mat cooling rate, and mixture design quantities. Numerous papers, symposia, and short courses have been given on the subject, but problems of obtaining the required in-place air void content persist. Although information available in the literature will not be summarized, the importance of asphalt properties and aggregate characteristics, as shown in Figure 13 (*17*), cannot be overlooked.

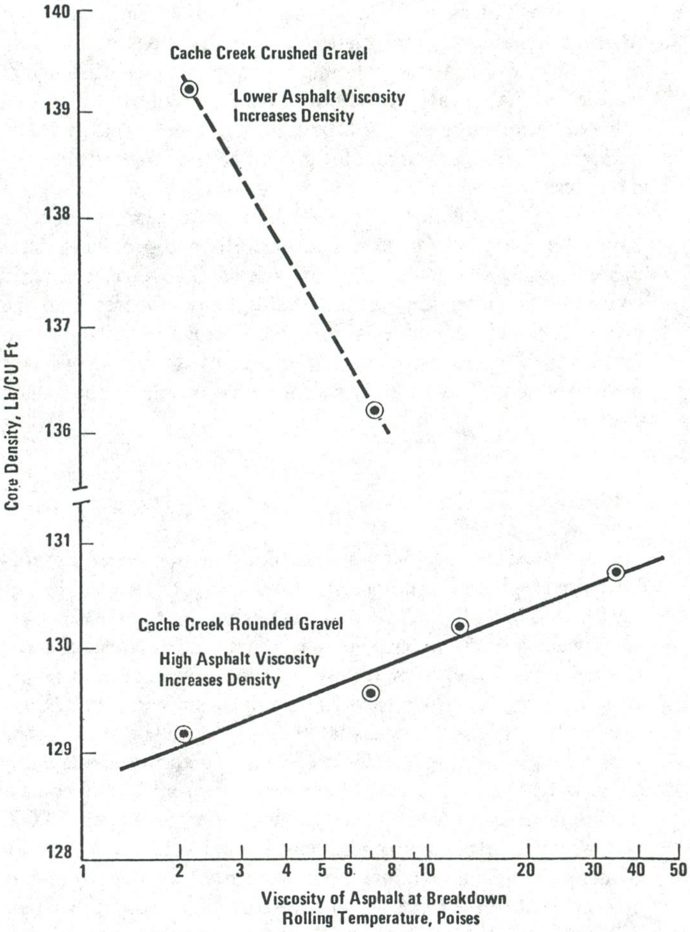

Figure 13. Effect of aggregate on compaction. (Source: Ref. 17)

STRUCTURAL DESIGN

Pavement structural design concepts have changed somewhat over the last 15 years. These changes have resulted in some early performance problems. Increased numbers of *thick asphaltic concrete sections* were placed in the late 1960's and the 1970's. In some cases lower quality aggregate and mixtures with reduced asphalt contents were placed in the lower layers of these thicker pavements. Because of inadequate test methods and specifications, water-susceptibility problems resulted on some projects. The cost of repairing these pavement failures was large.

Open-graded friction courses became popular in the late 1960's and early 1970's, as shown in Figure 14 (*29*). Improved skid resistance and fewer accidents were reported on many of these projects. Unfortunately, several of the open surfaces were placed on cracked pavements or old asphaltic concrete mixtures that were water susceptible. Because open-graded friction courses hold water on the pavement for an extended period of time, increased water contents in the asphalt mixtures, base course, subbase, and subgrade result, with an accompanying loss of strength and load-carrying ability. These factors, in turn, often caused complete disintegration of the entire pavement structure.

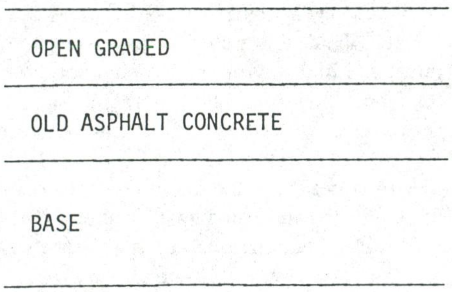

Figure 14. Open-graded friction course (Source: Ref. 29)

Pavement interlayers, as shown in Figure 15 (*29*), made with asphalt and fabrics and asphalt-rubber binders, have been used fairly extensively over the last 5 to 10 years. Slippage problems have resulted with this design when fabric interlayers have been used in combination with thin overlays on heavy traffic facilities. Specifications should be considered which define minimum thicknesses for overlays on fabrics.

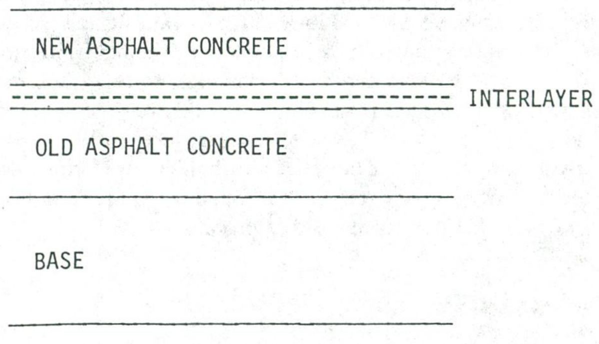

Figure 15. Pavement interlayers. (Source: Ref. 29)

Interlayers have proven to be good moisture barriers and, in some cases, have acted to increase the water content of the asphaltic concrete immediately below and/or above the interlayer. This water is a potential contributor to the pavement slippage problem previously discussed and to water-susceptibility problems in the asphaltic concrete mixtures.

Thin overlays of asphaltic concrete have been used extensively by a number of agencies as a result of limited funds and the desire to rehabilitate and maintain as many miles of roadway as possible. From a load-carrying standpoint, these thin layers were often inadequate. In addition, density is more difficult to achieve because the paving mixture cools more rapidly. Early performance problems including cracking, raveling, and slippage often resulted.

Overlays of asphaltic concrete on portland cement concrete pavements have also experienced performance problems. Slippage, cracking near joints, and moisture damage have been fairly common. The interface between the asphaltic concrete and the portland cement concrete is often wet. Moisture resistant materials must be placed at this interface. As expected, thin overlays have experienced more early performance problems than thick overlays.

TRAFFIC

Many existing specifications and construction control guidelines for asphaltic concrete mixtures were developed in the 1930's and 1940's and revised somewhat in the 1950's. Acceptance criteria were based on pavement performance observed during those same years. Traffic volumes, weights, and truck-tire pressures have increased substantially since the 1950's.

There is little argument that truck volumes have increased substantially over the last 25 to 30 years. In addition, allowable truck weights have increased in many states from 18,000 pounds on single axles to 20,000 pounds and from 32,000 to 34,000 pounds on tandem axles. The new federal fuel tax legislation requires that all states allow those heavier axles on the Interstate system. With these increases in both truck volumes and weights it is not unusual for Interstate highways to be designed to carry tens of millions of equivalent 18,000-pound axles.

Truck-tire pressures have also dramatically increased over the years and even higher truck-tire pressures are expected in the future. Most of the current pavement thickness design procedures and highway mixture design acceptance criteria are based on 70-psi pressures. Truck-tire pressures for several types of tires presently used on U.S. highways are in the 90- to 100-psi category. European and Japanese trucks operate with 120-psi tire pressures. Tire manufacturers are field testing tires with 135 psi (cold pressure readings). The effect of this increase in tire pressure is dramatic from both a theoretical and practical point of view. A substantial increase in permanent deformation or rutting can be predicted with those increases in tire pressures by theoretical computational methods.

Field observations also suggest that increased tire pressure may be a reason for the increased occurrence of pavement rutting. Pavements which exhibited little or no rutting for a period of 7 to 12 years can be rutted to unacceptable depths in a matter of weeks in the summer. A 12-year old tire test track in west Texas was rutted to a depth of 1 in., in a very confined wheel path in a period of 3 weeks, when trucks with 135-psi tire pressure were used. The trucks with high tire pressures had operated on the same test track through the winter months with no observable pavement distress problems.

ENVIRONMENT

Environmental conditions to which pavements have been subjected have changed very little, on the average. Years of relatively high or low temperatures and relatively high or low moisture have been experienced, however, and created localized problems. Specifications should recognize the extremes in temperature and moisture for a given area of the country and assume that these extremes will not vary significantly over the years.

There is also evidence that asphalts in hot desert regions harden more rapidly. Recent work (*30*) suggests that tighter asphalt aging requirements may be needed in desert areas.

SPECIFICATIONS AND QUALITY CONTROL

Specifications

Specifications for asphaltic concrete aggregates and properties have changed very little over the past 40 to 50 years. In the last 10 to 15 years asphalt cement specifications have changed. Many specifying agencies have changed from a penetration-based specification to a viscosity-based specification. In effect, the asphalt consistency control point was changed from 77 F to 140 F, as shown on Figures 16 and 17 (*31*). For the most part, crude sources and refining techniques have not been altered to meet these new specifications.

Paving asphalt specifications describe two of the three phases through which the asphalt passes during its service life. These phases are illustrated schematically in the temperature-viscosity curves shown in Figure 18 (*17*).

The first phase describes the asphalt as supplied to the user. Two viscosities are important—the viscosity at 135 C is useful for estimating the temperature at which the asphalt should be pumped and sprayed. The 60 C viscosity is used as one component in estimating the degree of hardening caused by heating. Other tests in this stage include solubility and flash point to satisfy purity, shipping, handling, and storage requirements.

Phase 2 represents the condition of the asphalt in the paving mixture during and shortly after construction. The asphalt hardens during production of the mix. The low temperature viscosity (or stiffness) and temperature susceptibility are used in mix design to mitigate thermal cracking in cold climates. The two viscosities at 60 C and 135 C are particularly important during construction. Aging rate is estimated by comparing the 60 C viscosity after artificial aging to the original viscosity. Normal specifications permit no more than a fivefold increase.

This upward shift of the Phase 2 temperature-viscosity curve may be simulated in the laboratory by use of a thin film oven aging test such as ASTM D1754 or ASTM D2872. But the shift that actually takes place on the job may or may not be represented by the thin film aging test. Construction practices, such as the use of drum mixers, mix temperature, time in surge bins, and filler type and amount, control the location of the Phase 2 curve.

The third phase represents the asphalt in a pavement after many years of service. The asphalt has aged, becoming harder and less temperature susceptible. The prediction of the location and slope of the Phase 3 curve has eluded technologists for years. There is no simple reliable laboratory test which predicts long-term aging, because asphalt aging rate in a pavement is dependent on asphalt quality, the amount of interconnected air voids, and the aggregate, particularly the fines. Air oxidizes the asphalt. Low voids mean slow asphalt aging; high voids, rapid aging. Voids in turn are controlled by the mix design, construc-

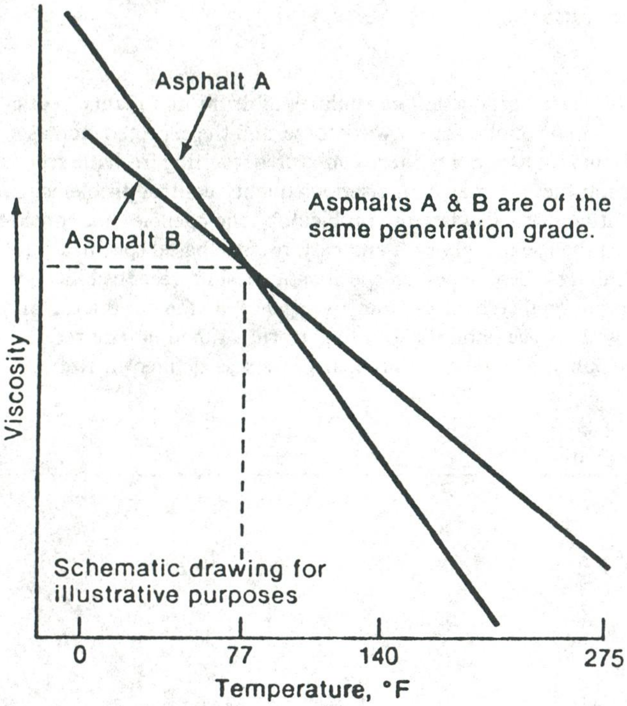

Figure 16. Variation in viscosity of two penetration-graded asphalts at different temperatures. (Source: Ref. 31)

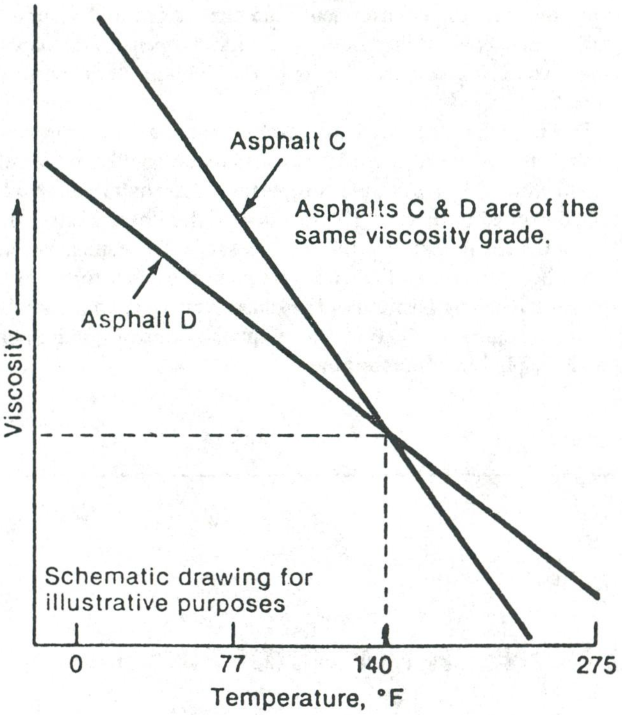

Figure 17. Variation in viscosity of two viscosity-graded asphalts at different temperatures. (Source: Ref. 31)

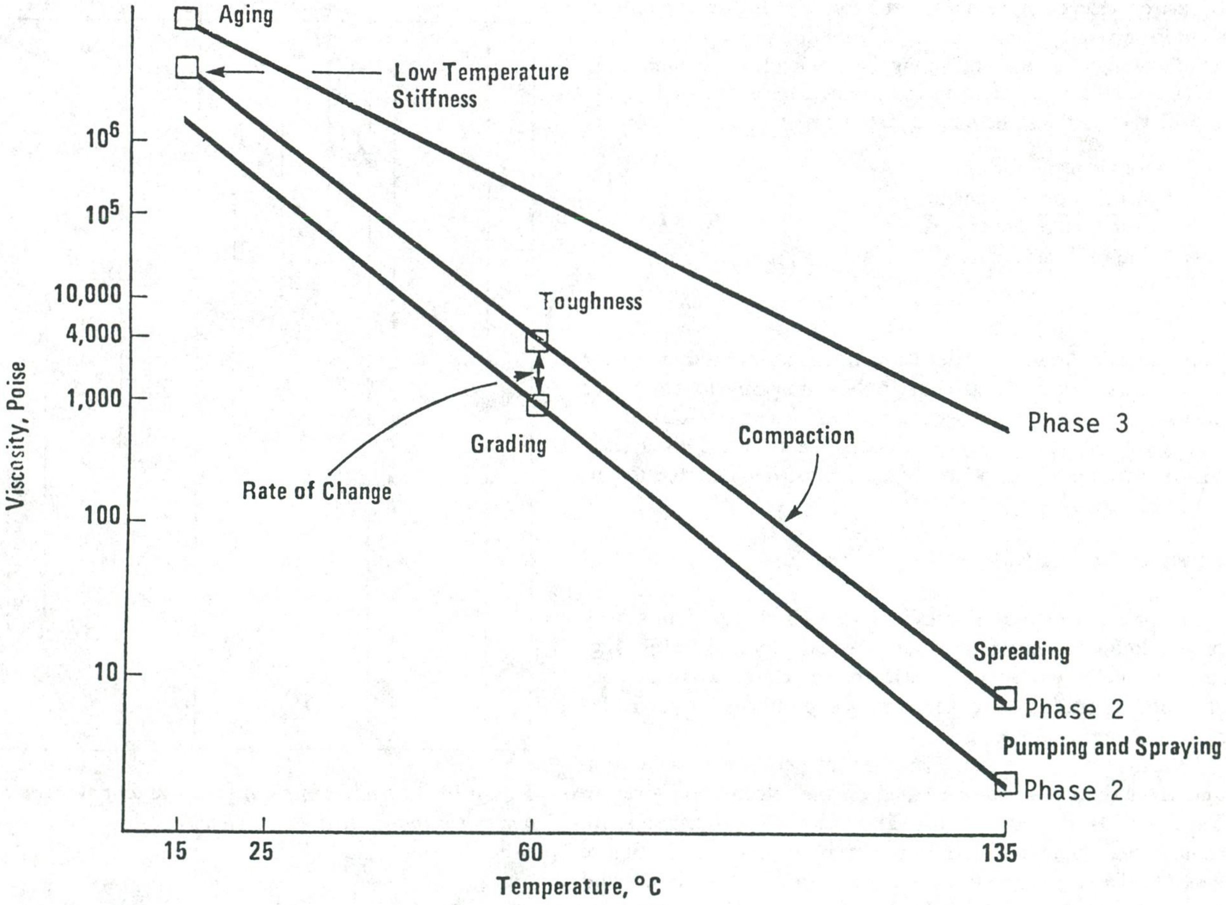

Figure 18. Functional paving asphalt specifications. (Source: Ref. 17)

tion practices, the environment, and the weight and volume of traffic. Hence, an understanding of what happens to the asphalt in a mix during construction is critical to long-term performance.

The need for improved asphalt cement specifications is apparent on review of Figure 18, the discussion above, and present specifications. For example, properties of asphalts below 77 F are controlled indirectly. The location of the Phase 2 curve may be controlled in part by the west coast AR specification and controlled partly by TFOT test results in the other forms of the specification. The position of the Phase 3 curve is not controlled by the asphalt specification but by quality control requirements on the asphaltic concrete mixture.

Quality Control

Increased production capabilities of drum mix plants, reductions in the public agency work force, and the expected increased demand for asphaltic concrete mixtures resulting from the recent federal fuel tax may create serious quality control problems. In an attempt to alleviate the problem, public agencies are considering the use of end result and performance-based specifications. Although these types of specifications shift responsibility for routine quality control from the agency to the contractor and thus allow the public agency to perform a function with reduced personnel, a number of problems exists as defined in Ref. 29.

CHAPTER THREE

ENGINEERING GUIDELINES

SELECTING AN ASPHALT CEMENT

Past experience is normally used for selecting an asphalt cement for a given paving project. Information presented in Chapter Two suggests that this may be an inadequate approach, inasmuch as a number of factors, which have changed in the last 10 years, should be considered. These factors include:

1. Asphalt properties.
2. Construction equipment.
3. Construction techniques.
4. Structural design.
5. Traffic.
6. Environment.

The engineer should consider these items, as a minimum, prior to final selection of the asphalt grade and aggregate which will provide the mixture properties desired. An approach for selecting an asphalt is briefly described in the following discussion. The reader is referred to Ref. 31 for a more detailed discussion.

Environmental Considerations and Traffic

Historically, selection of asphalts has been based primarily on maximum temperature conditions and expected traffic. Figure 19 was developed in an attempt to relate pavement construction operations and performance problems to particular ranges of temperature.

Selection of asphalt grade based on temperature consideration and layer thickness may be based on the information given in Table 4 (*32*). Selection of asphalts based on low temperature requirements may be based on information presented in Figure 20 (*33*). Debate persists as to which is an acceptable method to select asphalts based on low temperatures for a particular environment.

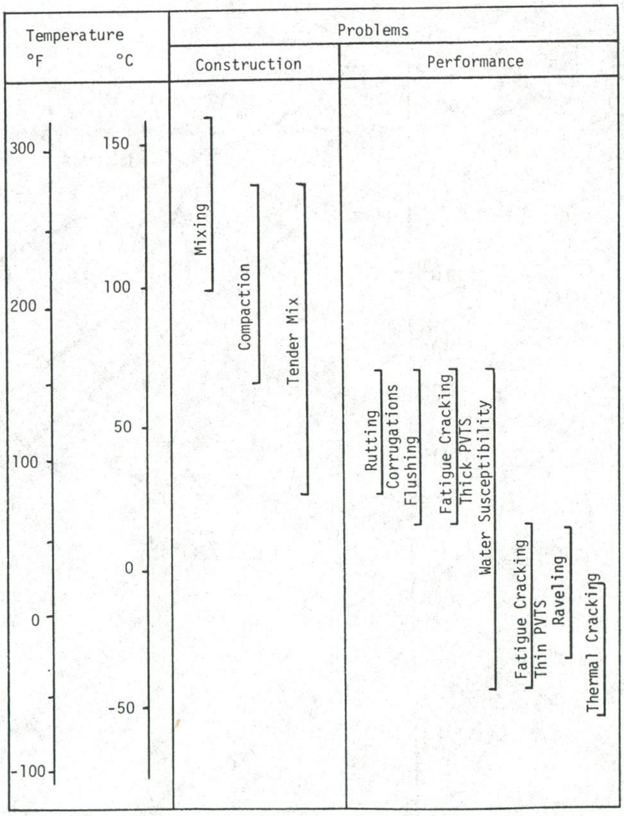

Figure 19. Critical temperature range for pavement construction and performance-related problems.

Table 4. Recommendations for selection of asphalt cement. (Source: Ref. 32)

Thickness of Asphalt Concrete, in.	Climate *	Asphalt Cement Grade		
		Penetration	Viscosity	
		AASHO M20 ASTM 3381	AASHO M226 ASTM 3381	Western States ASTM 3381
≤3	Cold[1]	200-300	AC-5	AR- 1000
	Moderate[2]	85-100	AC-10	AR- 4000
	Hot[3]	85-100	AC-10	AR- 4000
4-6	Cold	120-150	AC-5	AR- 2000
	Moderate	60-70	AC-20	AR- 4000
	Hot	60-70	AC-20	AR- 8000
>7	Cold	120-150	AC-5	AR- 2000
	Moderate	60-70	AC-20	AR- 8000
	Hot	40-50	AC-40	AR- 16000

[1] Normal minimum daily temperature of 10F or less; for extremely low temperature special studies are recommended.

[2] Normal maximum daily temperature of 90F or less.

[3] Normal maximum daily temperature greater than 90F.

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*As per U. S. Weather Bureau climatological reports.

STRUCTURAL DESIGN AND TRAFFIC

Traffic and load-carrying capability of the underlying materials will largely control thickness of the asphaltic concrete layer; however, the necessity for placing interlayers or other special features and the desired properties of the asphaltic concrete mixtures should be considered. Mixture properties such as stability, durability, flexibility, tensile strength, fatigue resistance, skid resistance, and permeability should be optimized for a given paving project. Table 5 indicates the relative amount and type of asphalt desired to maximize individual properties. For example, high asphalt contents are desirable for good durability, flexibility, tensile strength, fatigue resistances, and low permeability, while low asphalt content is desired for stability and skid resistance. Obviously a balanced design must be obtained for a particular application. The general philosophy is to use as much asphalt as possible while maintaining the desired stability level and keeping air voids within acceptable limits of 3 to 5 percent as determined after a specified laboratory compactive effort.

In certain areas of the country increased truck traffic, higher tire pressures, and the use of thicker pavements demand the use of harder asphalts for improved stability. One should remember that aggregates can be selected to provide improved stability, thereby affording the use of softer asphalts and preserving the pavement's resistance to low temperature cracking.

As mentioned previously, the use of interlayers and overlaying of portland cement concrete require that paving mixtures have good resistance to water susceptibility. Water susceptibility properties should be tested on all mixtures.

Construction Equipment and Techniques

Preliminary selection of the type of asphalt should be based on information presented in Tables 4 and 5 and Figure 20, and as discussed above. Final selection should be made after considering the type of construction equipment and techniques that will be used and understanding their effects on asphalt properties and mixture performance during construction and service life.

As noted earlier, the following construction-related factors will affect asphalt properties, type of mixing equipment, type and sequence of compaction, type of quality control equipment,

Table 5. Relative effect of asphalt cement type and amount on properties of asphaltic concrete.

Mixture Property	Relative Asphalt Cement Content	Relative Consistency of Asphalt Concrete
Stability	low	hard
Durability	high	soft
Flexibility	high	soft
Tensile Strength	high	hard
Fatigue Resistance	high	hard*
Skid Resistance	low	hard
Imperviousness	high	–

*For thick pavement (greater than 4 inches) hard asphalts are suggested for this pavement; less than 2 inches, soft asphalts are suggested.

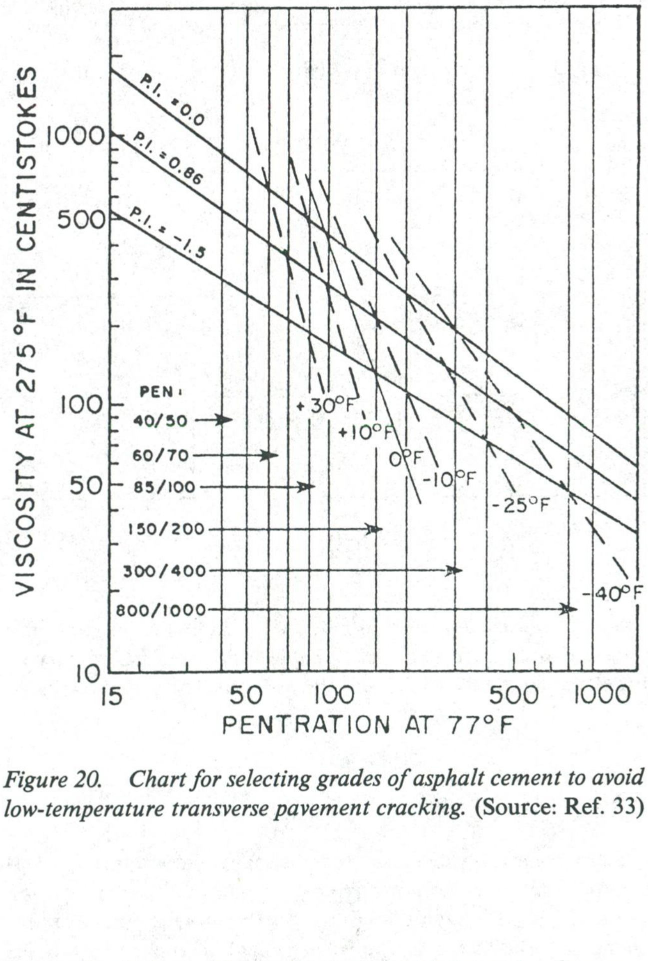

Figure 20. Chart for selecting grades of asphalt cement to avoid low-temperature transverse pavement cracking. (Source: Ref. 33)

Table 6. Effect of construction equipment and construction techniques on asphalt cement properties.

Construction Related Factors	Usual Effect On Asphalt Consistency	Mechanism	Reference
Drum Mixer Versus Batch Plant	Soften*	Lower mixing temperature are utilized in drum mixers. Possible unburned fuel contamination.	Figures 3, 4, 5 and 6
Vibratory Roller Versus Pneumatic	Harden	Vibratory equipment may not seal surface and pavement is permeable to air and water thus more rapid harden during service.	
Bag House Versus Wet Washer System	Harden	Baghouse fines are returned to mix which increases the apparent viscosity of the asphalt.	Figures 7 and 8
Transport of Asphalt in Contaminated Transport	Soften	Residual products in transport (often heavy fuel oil or cutback) soften asphalts.	
Mixing of Asphalt in Storage	Soften	Blending of two crudes of same grade may chemically interact to form an out of grade product, separation of asphalts would also occur.	Figure 10
Use of Antistrip Chemical in Asphalt	Soften	Chemical interaction usually result in a softening of the asphalt.	Figures 11, 12 and Table 3.
High Mixing Temperature	Harden	Higher mixing temperatures promote more rapid oxidation and volatilization of asphalt.	Figure 3
Hot Storage of Asphalt Concrete	Harden	Prolonged storage of hot mixes will promote oxidation and volatilization of asphalt.	

*Excessive hardening can occur if proper flite maintenance is not practiced and/or production quantities are low.

transport and storage of asphalt, use of additives, mixing temperature and hot storage time. Table 6 presents a summary of the effects of these variables on the properties of paving asphalts.

Temperature Susceptibility

Data reviewed previously indicate that temperature susceptibility of asphalts from a given refinery have changed over the years. Thus, the paving engineer and technician must expect changes in the future and must be prepared to cope with these changes. The magnitude and significance of the changes on construction are shown on Figure 1. For example, Figure 1 suggests that mixing and compaction temperatures would have to be adjusted by about 20 to 25 F if property changes in the asphalts occurred during a construction project as indicated on this figure. Data published by The Asphalt Institute indicate that mixing of asphalt cement and aggregates should be performed at a temperature where the viscosity of the asphalt cement is 1.70 to 0.20 poises. Compaction should occur at a temperature when the viscosity of the asphalt cement is 2.80 to 0.30 poises.

Asphalts shown on Figure 21 meet the specification grade. There is ample evidence to suggest that asphalts of the same specification grade will exhibit different behavior. Figure 21 illustrates the difference in AC-20 asphalts from the same market area (*1*). If a contractor used these asphalts on the same project, mixing and compaction temperatures would have to be adjusted 35 to 40 F. Blending of these two asphalts in a single storage tank at the construction site could also produce an asphalt that would fall outside of the specification as shown on Figure 10.

Figure 22 shows the low temperature behavior of AC-10 asphalts from Texas (*32*). Predicted cracking temperatures range from 20 F to −15 F for the AC-10 asphalt cements. It is clear that the engineer not only must select the grade of asphalt for a given project, but must also be aware of the properties the asphalt will actually possess during service.

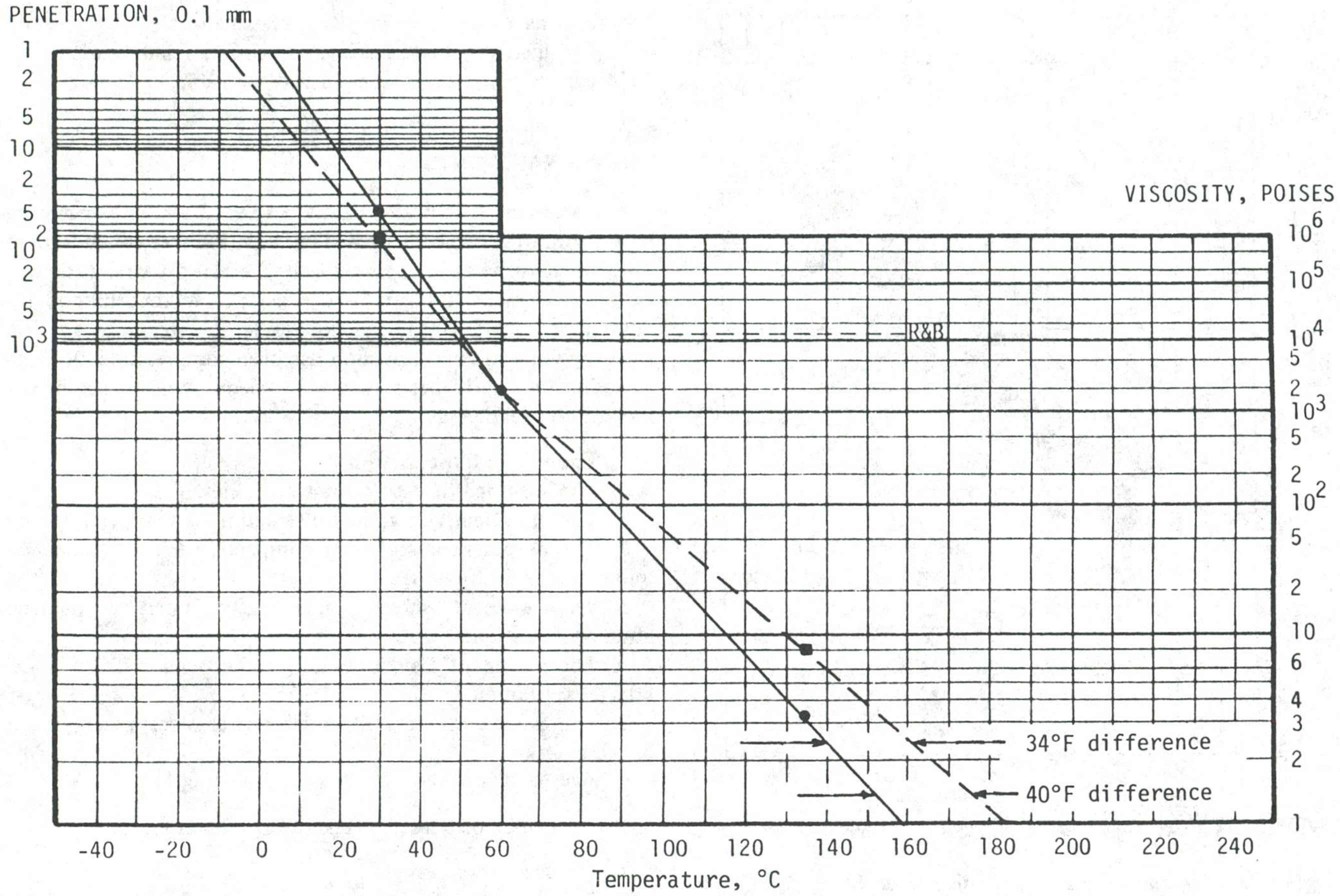

Figure 21. Range of AC-20 properties in a northwest Texas market area. (Source: Ref. 21)

Asphalt Hardening

Figure 18 illustrates the significance of asphalt hardening during both hot mix hardening (Phase 2) and in service during performance (Phase 3). The amount of hardening during hot mixing, as simulated by the thin film oven test, is greatly dependent on the source of the asphalt (Fig. 23 (*1,6*)). This must be considered together with the mixing equipment prior to the final selection of the grade of the asphalt cement as the location of the Phase 2 line will determine the laydown and compaction temperatures and the early performance of the pavement.

Location of the Phase 3 line on Figure 18 has eluded some asphalt technologists. Its location is dependent on at least two major factors, air void content or permeability of the asphaltic concrete mix and asphalt source. The location of this Phase 3 line controls one factor contributing to the performance of asphaltic concrete.

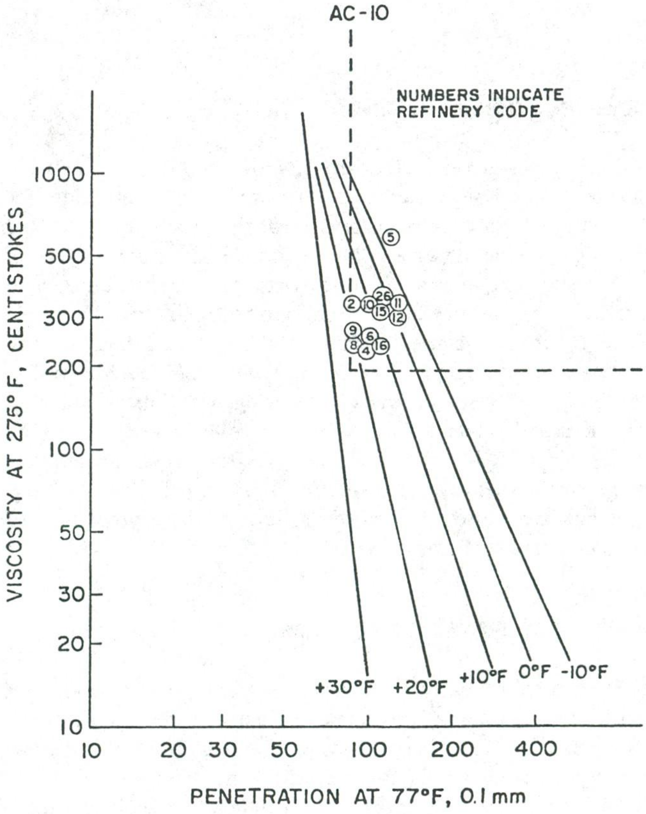

Figure 22. Allowable minimum temperature for AC-10 asphalts. (Source: Ref. 32)

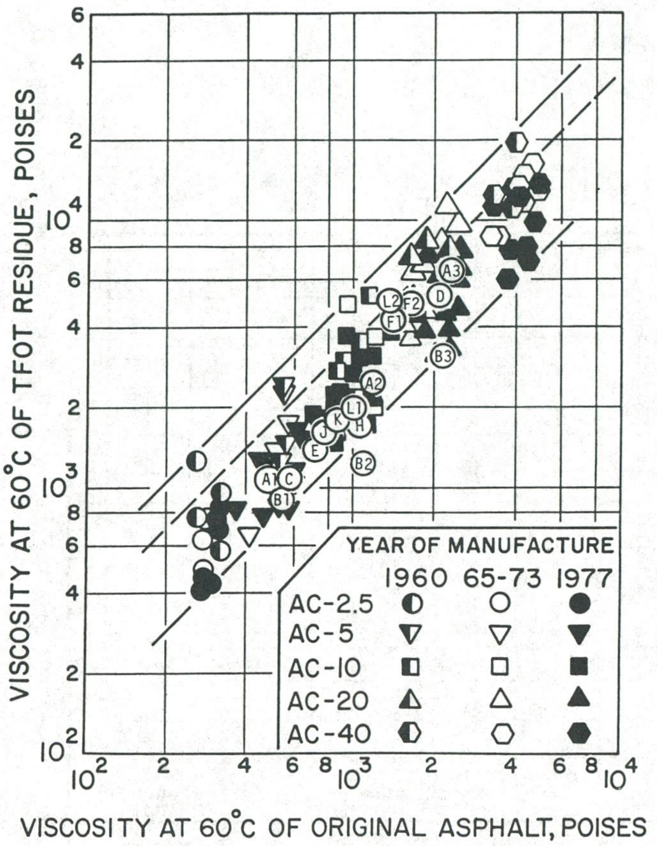

Figure 23. Relationship between viscosity at 140 F (60 C) for original and heated asphalt cements. (Source: Refs. 1 and 6)

CONSTRUCTION PROBLEMS

The Barber-Greene Company (*34, 35*) and The Asphalt Institute (*36*), among others, have developed excellent guides for "trouble shooting" mixing and laydown problems associated with the production of asphaltic concrete pavements. Types of deficiencies and probable causes that may be encountered in producing asphaltic concrete mixtures are summarized in Table 7 (*36*). Probable causes of mat problems during laydown operations are presented in Tables 8, 9 and 10. Table 8 identifies the broad problems of cracking, tearing, wavy mats, and segregation, and relates them to finisher, roller, truck, plant, and mix variables (*34*). Tables 9 and 10, from Refs. 34 and 36, respectively, identify more specific laydown problems and suggest possible causes; related discussions of these problems can be found also in Refs. 34 and 36.

FIELD PERFORMANCE PROBLEMS

Premature or early field performance problems have been noted on a number of projects constructed in the last 10 years. The usual manifestation of these problems is pavement raveling, rutting, or cracking. These and other early performance problems including tender mixes can be related to asphalt cement properties as well as to numerous other factors (*37*). Types of pavement distress, their causes, and possible rehabilitation and maintenance actions are summarized on Table 11 (*38*).

TENDER PAVEMENTS

A discussion specifically directed toward tender pavements appears appropriate because a significant number of tenderness "problems" have been reported over the last 5 years. A tender mix or pavement has very low resistance to deformation by "punching" loads and/or scuffs under horizontally applied shearing loads after compaction has been completed (*39*). Construction and early performance problems with tender mixes include the following;

1. The mix is difficult to roll.
2. The specified density cannot be achieved.
3. The pavement ruts after construction is complete.
4. The pavement is soft after compaction and will displace under the heel of a shoe.
5. The pavement "shoves" under traffic, sometimes months after construction.
6. The pavement distorts under traffic, usually fairly soon after construction.
7. The pavement "scuffs" under power steering or severe braking action.
8. The pavement indents under a punching load (*39*).

Likely causes of tender mixes are given as follows:

1. Incorrect mix design.
2. Excessive middle-size sand in the mix; characterized by a hump in the grading curve for the material passing the No. 4 sieve.
3. Insufficient amounts of material passing the No. 200 sieve.
4. Grade of asphalt used in the mix too soft (i.e., viscosity of the asphalt used in the mix too low).
5. Ambient temperature too high.
6. Insufficient density of completed pavement (a number of things may contribute to this factor).
7. Excess fluids in mix (asphalt plus moisture) (*39*).

From the foregoing discussion it is apparent that "tenderness" as used in the paving industry has one or both of two general meanings; tenderness during construction and tenderness after construction.

Tenderness During Construction

Tenderness of an asphaltic concrete mixture during construction refers to a mixture that will not densify properly at normal compaction temperatures using conventional equipment. The mixture may shove excessively under steel wheel rollers or leave depressions behind pneumatic rollers. This problem normally results from a lack of interparticle friction or shear strength such as that brought about by aggregate properties including smooth, rounded particles, high sand content, small top size, low filler content, and so on. Where aggregate problems already exist, the problem will be compounded by an asphalt of high temperature susceptibility. Such an asphalt may meet specifications at 140 F; however, at 275 F the viscosity may be sufficiently low to reduce the shear resistance of the asphalt paving

Table 7. Possible causes of deficiencies in plant-mix pavements. (Source: Ref. 36)

Types of Deficiencies That May Be Encountered in Producing Hot Plant-Mix Paving Mixtures.	Asphalt Content Does Not Check Job Mix Formula	Aggregate Gradation Does Not Check Job Mix Formula	Excessive Fines in Mix	Uniform Temperatures Difficult to Maintain	Truck Weights Do Not Check Batch Weights	Free Asphalts on Mix in Truck	Free Dust on Mix in Truck	Large Aggregates Uncoated	Mixture in Truck Not Uniform	Mixture in Truck Fat on One Side	Mixture Flattens in Truck	Mixture Burned	Mixture Too Brown or Gray	Mixture Too Fat	Mixture Smokes in Truck	Mixture Steams in Truck	Mixture Appears Dull in Truck
Poor Quality Aggregates	A	A	A					A	A							A	
Aggregates Too Wet				A				A					A			A	
Inadequate Bunker Separation		A	A														
Aggregate Feed Gates Not Properly Set	A	A	A									A					
Over-rated Drier Capacity				A				A					A			A	
Drier Set Too Steep				A				A					A			A	
Improper Drier Operation				A				A				A	A		A	A	A
Temp. Indicator Out of Adjustment				A				A				A	A		A	A	A
Aggregate Temperatures Too High												A			A		A
Worn Out Screens		A															
Faulty Screen Operation		A	A						A				A				
Bin Overflows Not Functioning		A	A						A								
Leaky Bins		A	A		B				A								
Segregation of Aggregates in Bins		A	A						A								
Carryover in Bins Due to Overloading Screens		A	A						A								
Aggregate Scales Out of Adjustment	B	B	B		B	B			B					B			
Improper Weighing by Operator	B	B	B		B	B			B					B			
Feed of Mineral Filler Not Uniform		A	A						A					A			
Insufficient Aggregates in Hot Bins		A	A						A					A			
Improper Weighing Sequence					B		B		B	B							
Insufficient Asphalt	A							A					A				A
Too Much Asphalt	A					A					A			A			
Faulty Distribution of Asphalt to Aggregates	A					A		A	A	A	A			A			
Asphalt Scales Out of Adjustment	B					B		B	B		B		B	B			
Asphalt Meter Out of Adjustment	C					C		C	C		C		C	C			
Underaise or Oversize Batch	B	B	B		B	B		B		B	B		B	B			
Mixing Time Not Uniform	B		B					B	B	B							
Improperly Set or Worn Paddles	A	A				A		A	A	A							
Faulty Dump Gate		A					B		B								
Asphalt and Aggregate Feed Not Synchronized	C	C	C			C		C	C		C		C	C			
Occasional Dust Shakedown in Bins		A	A						A								
Irregular Plant Operation				A				A	A	A	A	A	A	A	A	A	A
Faulty Sampling																	

A-Batch and Continuous Type Plants.

B-Batch Plants only.

C-Continuous Plants only.

Table 8. Causes of mat deficiencies. (Source: Ref. 34)

		CRACKING	TEARING	WAVY MATS	SEGREGATION
MIX	Excess #200 Mesh Material	X			
	Too Hot or Too Cold	X			
	Too Dry or Too Rich		X		
	Lack of Fines		X		
	Too Cold		X		
	Improper Mat Thickness VS. Aggregate Size Ratio		X		
PLANT	Mixing Temperature Fluctuations			X	
	Segregated Aggregate Stockpile				X
	Poor Cold Feed				X
	No. 1 Hot Bin Segregation				X
	Insufficient Dry Mix Time				X
TRUCKS	Truck Brake set too Hard			X	
	Improper Loading of Truck				X
ROLLER	Improper Rolling			X	
	Over-rolling Where Base Deflects	X			
	Turning too Abruptly	X			
	Reversing too Abruptly	X		X	
FINISHER	Build-up in Hopper Sides				X
	Flushing of Fines				X
	Screed Over-control			X	
	Over-loading Spreading Screws			X	
	Screed Rams Holding			X	
	Condition of Tamper or Screed		X		
	Adjustment of Tamper or Screed		X		

mixture. A mixture of this type may be accommodated by lowering the compaction temperature. Low plant temperatures, particularly with drum mix plants, can contribute to this type of problem by reducing the asphalt hardening that normally occurs in the plant. One may also consider a harder grade of the asphalt or the addition of filler such as limestone screenings, lime, or cement to reduce the tenderness during construction. Difficulty in compacting a tender mix is a result of overstressing the mix. This problem can sometimes be accommodated by using pneumatic rollers with reduced tire pressure.

Tenderness After Construction

Tenderness of an asphaltic concrete mixture after construction usually disappears within a few weeks and is most likely caused by a slow setting asphalt. This mixture may also be tender (difficult to compact) during construction. The resulting pavement will scuff and deform under point loads or shear forces for a few days or weeks but will eventually "set up" and may then be expected to perform quite well. The use of slow-setting asphalts may cause this problem. These types of asphalts are not necessarily highly temperature susceptible and thus may be more difficult to accommodate than one that is highly temperature susceptible. The addition of filler such as lime, cement, or limestone screenings may help provide some stability to this mixture during the compaction and setting stages. If tenderness after construction is not asphalt-related, it is probably due to lack of adequate densification during the conventional compaction process. This problem may be diminished by continued rolling of the finished pavement using pneumatic rollers during the hottest part of the day. Table 12 summarizes factors which influence tender pavements.

Identifying Tender Mixes

It is desirable to identify tender mixes prior to the start of construction in order that materials and/or design parameters may be altered. Table 12 indicates that mixtures which contain one or more of the following characteristics should be suspect:

1. Large proportions of sand sizes.
2. Small quantities of minus No. 20 material.
3. Small maximum size aggregate.
4. Smooth, rounded aggregates.
5. Highly temperature susceptible asphalts.
6. Slow-setting asphalts.
7. Less than anticipated hardening during hot mixing.
8. High fluids contents.

The development of mixture testing techniques to identify tender mixes prior to construction has been attempted (*40*).

Ideally, the field engineer would like to recognize that a mixture will be difficult to compact and/or will be slow setting after construction 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 mixtures and construction factors which 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. Those approaches are discussed in the following paragraphs (*40*).

Material, Mixture, and Construction Factors Contributing to Tender Mixes

Figure 24 is a rating scale which can be used to identify the material, mixture, and construction factors which contribute to tender mixes. Important aggregate factors are (1) shape, and surface textures of both the coarse aggregate and fine aggregate;

Table 9. Mat problem trouble-shooting guide. (Source: Ref. 34)

	CAUSES																																					
PROBLEM	Fluctuating Head of Material	Feeder Screws Overloaded	Finisher Speed Too Fast	Too Much Lead Crown in Screed	Too Little Lead Crown in Screed	Overcorrecting Thickness Control Screws	Excessive Play in Screed Mechanical Connection	Screed Riding on Lift Cylinders	Screed Plates Worn Out or Warped	Screed Plates Not Tight	Cold Screed	Moldboard on Strikeoff Too Low	Running Hopper Empty Between Loads	Feeder Gates Set Incorrectly	Kicker Screws Worn Out or Mounted Incorrectly	Incorrect Nulling of Screed	Screed Starting Blocks Too Short	Screed Extensions Installed Incorrectly	Vibrators Running Too Slow	Grade Control Mounted Incorrectly	Grade Control Hunting (Sensitivity Too High)	Grade Control Wand Bouncing on Reference	Grade Reference Inadequate	Sitting Long Period Between Loads	Improper Joint Overlap	Improper Mat Thickness for Max. Agg. Size	Trucks Bumping Finisher	Truck Holding Brakes	Improper Base Preparation	Improper Rolling Operation	Reversing or Turning Too Fast of Rollers	Parking Roller on Hot Mat	Improper Mix Design (Aggregate)	Improper Mix Design (Asphalt)	Mix Segregation	Moisture in Mix	Variation of Mix Temperature	Cold Mix Temperature
Wavy Surface — Short Waves (Ripples)	✓	✓	✓				✓	✓		✓										✓	✓	✓	✓						X	X			X	X	X		X	
Wavy Surface — Long Waves	✓	✓				✓	✓	✓					✓	✓					-	✓			✓	✓			X	X	X		X	X			X		X	
Tearing of Mat — Full Width			✓						✓		✓															X							X	X	X	X	X	X
Tearing of Mat — Center Streak					✓				✓		✓			✓	✓																							X
Tearing of Mat — Outside Streaks				✓					✓		✓	✓		✓				✓																				X
Mat Texture — Nonuniform	✓	✓	✓					✓	✓	✓	✓		✓					✓	✓					✓		X			X				X	X	X		X	X
Screed Marks							✓																				X	X										
Screed Not Responding to Correction			✓				✓	✓		✓										✓						X											X	X
Auger Shadows		✓																															X	X	X			
Poor Precompaction			✓					✓											✓							X			X									X
Poor Longitudinal Joint	✓	✓				✓		✓												✓	✓	✓			✓					X								X
Poor Transverse Joint		✓					✓	✓		✓						✓	✓													X								X
Transverse Cracking (Checking)																													X	X			X	X		X	X	
Mat Shoving Under Roller																													X	X	X		X	X		X	X	
Bleeding or Fat Spots in Mat																																	X	X		X	X	
Roller Marks																													X	X	X	X					X	
Poor Mix Compaction																													X	X	X	X	X	X		X	X	X

1. Find problem above.
2. Checks indicate causes related to the paver. X's indicate other problems to be investigated.

NOTE: Many times a problem can be caused by more than one item, therefore, it is important that each cause listed is eliminated to assure solving the problem.

(2) quantity of sand size materials; (3) filler or minus No. 2 sieve fraction; 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 the 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 mixes. 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) the presence of moisture.

As discussed previously, all of 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 have tenderness problems regardless of asphalt properties or construction operations. Mixtures with subrounded aggregates with smooth surface textures, relative high sand controls (gap-graded), and with low filler content will often be tender when low viscosity asphalts are used which contain low asphaltene contents, and when mixing operations are performed at low temperatures and/or the anticipated hot mix hardening of the asphalt in the mixer is not achieved.

Ideally, a mathematical equation would be developed with the above-listed material, mixture, and construction variables. Each of these variables would be properly "weighted" to indicate their relative influence on developing tender mixes. A sufficiently large data base was not developed on this project to develop a reliable equation. A large and continuous research effort would be needed to develop such an equation. In this interim, the field engineer should assign the proper importance of each identified factor based on his experience.

Laboratory Tests to Identify Tender Mixes

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

1. Resilient modulus of mixtures.
2. Indirect tensile 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. Asphalt 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 on mixtures and the asphaltene content of the asphalt cement are the most meaningful tests for identifying potential tender mixes in the laboratory.

Criteria for each of these tests are presented in Table 13. On the basis of the project results, it is suggested that the indirect tensile test and/or the resilient modulus test be performed on laboratory-mixed and laboratory-compacted samples, using the

Table 10. **Possible causes of imperfections in finished pavements. (Source: Ref. 36)**

Types of Pavement Imperfections That May Be Encountered In Laying Hot Plant Mix Paving Mixtures.	Bleeding	Brown, Dead Appearance	Rich or Fat Spots	Poor Surface Texture	Rough Uneven Surface	Honeycomb or Ravelling	Uneven Joints	Roller Marks	Pushing or Waves	Cracking (Many Fine Cracks)	Cracking (Large Long Cracks)	Rocks Broken by Roller	Tearing of Surface During Laying	Surface Slipping on Base
Insufficient or Non-uniform Tack Coat					X				X					X
Improperly Cured Prime or Tack Coat					X				X					X
Mixture Too Coarse				X	X	X	X					X	X	
Excess Fines in Mixture				X				X	X	X				X
Insufficient Asphalt		X				X				X			X	
Excess Asphalt	X		X					X	X					X
Improperly Proportioned Mixture	X		X	X	X	X		X	X	X		X	X	X
Unsatisfactory Batches in Load	X		X	X	X	X			X					
Excess Moisture in Mixture		X							X					X
Mixture Too Hot or Burned		X											X	
Mixture Too Cold				X	X	X	X	X				X	X	X
Poor Spreader Operation				X	X	X	X		X			X	X	
Spreader in Poor Condition				X	X	X	X		X			X	X	
Inadequate Rolling				X	X	X	X	X						X
Rolling at Wrong Time				X	X	X	X	X	X	X		X		X
Over-Rolling				X						X	X	X		X
Rolling Mixture When Too Hot				X	X		X	X	X	X		X		
Rolling Mixture When Too Cold				X	X	X	X	X						X
Roller Standing on Hot Pavement					X			X						
Overweight Rollers					X			X	X	X	X	X		X
Roller Vibration					X				X					
Unstable Base Course					X		X		X	X	X		X	X
Excessive Moisture in Subsoil										X	X			X
Excessive Prime Coat or Tack Coat	X		X											X
Poor Handwork Behind Spreader				X	X	X	X							
Excessive Hand Raking				X	X	X	X		X					
Labor Careless or Unskilled				X	X	X	X	X						
Excessive Segregation in Laying			X	X	X	X	X						X	
Faulty Allowance for Compaction							X							
Operating Finishing Machine Too Fast				X	X								X	
Mix Laid in Too Thick Course									X					
Traffic Put On Mix While Too Hot									X					

criteria developed in Table 13 for the following specific conditions:

1. Gyratory compaction (modified or standard).
2. Air void content at standard or higher.
3. Test temperature of 104 F 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 conditions.

Table 11. Pavement distress and possible causes and rehabilitation alternatives. (Source: Ref. 38)

Type of Distress	Possible Causes	Rehabilitation Alternatives
Rutting	Structural deficiency HMAC mix design Asphalt cement properties Stability of pavement layers Compaction (density) - all layers	Cold milling including profile requirements, with or without overlay Heater scarification with surface treatment or thin overlay Replacement (particularly applicable to corrugations in localized areas)
Raveling	Low asphalt content Excessive air voids in HMAC Hardening of asphalt Water susceptibility (stripping) Aggregate characteristics Hardness and durability of aggregate	Dilute emulsion or rejuvenating "fog" seal Seal coat with aggregate Slurry seal Thin HMAC overlay
Flushing (Bleeding)	High asphalt content Excessive densification of HMAC during construction or by traffic (low air void content) Temperature susceptibility of asphalt (soft asphalt at high temperatures) Excess application of "fog" seal or rejuvenating materials Water susceptibility of underlaying asphalt stabilized layers together with asphalt migration to surface	Overlay of open graded friction course Seal coat (well designed with good field control during construction) Cold milling with or without seal coat or thin overlay Heater-scarification with seal coat or thin overlay Heat surface and roll-in coarse aggregate
Alligator Cracking	Structural deficiency Excessive air voids in HMAC Asphalt cement properties Stripping of asphalt from aggregate Construction deficiencies	Seal coat Replacement (dig-out and full depth HMAC replacement in failed areas) Overlay of various thicknesses with or without special treatments to minimize crack reflection Recycle (central plant on in-place) Reconstruction
Longitudinal Cracking	Load Associated Structural deficiency Excessive air voids in HMAC Asphalt cement properties Stripping of asphalt from aggregate Aggregate gradation Construction deficiencies Non Load Associated Volume change potential of foundation soil Slope stability of fill materials Settlement of fill or in-place materials as a result of increased loadings Segregation due to laydown machine Poor joint construction Other construction deficiencies	Crack sealing Seal coat (applied to areas with cracking) Replacement (dig-out and replace distressed areas) Thin overlay with special treatment to seal cracks and minimize reflection cracking Asphalt-rubber membrane with aggregate seal or thin overlay Heater-scarification with a thin overlay
Transverse Cracking	Hardness of asphalt cement Stiffness of HMAC Volume changes in base and subbase Unusual soil properties	Crack sealing Seal coat Overaly with special treatment to seal cracks and minimize reflection cracking Asphalt-rubber membrane with aggregate seal or thin overlay Heater scarification with a thin overlay
Roughness	Presence of physical distress (cracking, rutting, corrugations, potholes, etc.) Volume change in fill and subgrade materials Non-uniform construction	Overlay Cold milling with or without overlay Heater scarification with overlay Heater planning with overlay (primarily for local areas and areas with corrugations) Recycle (central plant or in-place)

Table 12. Factors influencing tender pavements.

Material or Mixture Variable	Discussion
Aggregate Gradation	Avoid large proportions of sandsize particles. Minus No. 200 material should be greater than 4 percent. Mineral filler can add stability to a mixture. Small maximum size aggregate mixes have a greater tendency to be tender.
Aggregate Type	Smooth, rounded aggregate particles are most likely to produce a tender mixture. Sand sized crushed particles can add stability to a mixture.
Asphalt Properties	Highly temperature susceptible asphalts can aggrevate tenderness problems. Slow setting asphalts can cause tenderness problems. Less than anticipated hardening of the asphalt during hot mix hardening can cause tenderness problems.
Asphalt Content	High asphalt content can aggravate tenderness problems. High fluids content (asphalt plus water) can cause tenderness problems.

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 (41)	>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.

Figure 24. Rating scale to identify tender mixtures.

Table 13. Criteria for tough and tender mixes (*40*).

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 T.S.** @ 104°F @ 24 hrs	> 7,000 psi > 5 psi	< 6,000 psi < 5 psi
Modified Compaction of Field Mixtures (∿ 8-10% air voids)	M_R @ 104°F @ 24 hrs T.S. @ 104°F @ 24 hrs	> 30,000psi > 20 psi	< 20,000psi < 15 psi
Standard Gyratory Compaction of Remolded Field Cores	M_R @ 104°F @ 90 min T.S. @ 77°F @ 90 min M.S.*** @ 140°F @ 90 min	>130,000psi > 165 psi > 1,000 lb	<125,000psi < 140 psi < 2,500 lb

*M_R = Resilient Modulus

**T.S. = Tensile Strength

***M.S. = Marshall Stability

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