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16. Abstract

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ASPHALT PROPERTIES AND PAVEMENT PERFORMANCE

by

Cindy K. Adams

and

Richard J. Holmgreen

Research Report 287-4F
Research Study Number 2-9-80-287
Desirable Asphalt Properties

Sponsored by

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August 1986

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas

METRIC CONVERSION FACTORS

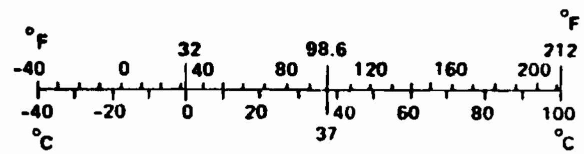
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ABSTRACT

Three experimental test roads were constructed using asphalts from five different refineries. Samples were fabricated in the laboratory and field cores were obtained in an attempt to correlate standard laboratory test data to field performance.

New laboratory tests, such as gel permeation chromatography and dissipated strain energy, were investigated for their potential in characterizing asphalt cements.

KEY WORDS

Asphalt properties, field performance, gel permeation chromatography, dissipated strain energy.

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CHAPTER I

INTRODUCTION

Background

Numerous asphalt concrete pavement performance problems including raveling, cracking and rutting have been recently ascribed to poor quality asphalt concrete. According to field reports, asphalts experience early hardening, are brittle and have poor adhesion in the presence of water.

The 1973 oil embargo has prompted the claim by many pavement technologists that much of the asphalt currently being produced is inferior in quality and is the cause of many field failures. Typical complaints are, "the asphalt is not as sticky as it used to be", or "the refineries are taking out all the good stuff". In addition, field personnel are convinced that the present asphalt specification tests, which are routinely performed, do not identify the important properties that affect field construction and influence pavement performance.

The complaints registered by the field engineers should not go unheeded. Indeed, the asphalt cements have changed in recent years, since crude sources and refining techniques have changed. This is due, in part, to the United States' dependency on foreign crude which presents problems to the asphalt manufacturers. Some of these problems are discussed below:

1. A larger number of crude sources are often required to supply a refinery. This constant change in crude source has created some uniformity problems and has required blending of crudes.
2. Major manufacturers have little assurance that a foreign crude source will be available for an extended period of time.
3. Crude sources have changed over the last 10 years, and in some cases present day sources do not produce a desirable asphalt.

4. Oil companies are, as never before, requiring that all product lines, including asphalt, produce their proportion of profits. Thus, several alternatives for the bottom of the barrel from which asphalt is produced are seriously considered.
5. The bottom of the barrel, hence asphalt, has become a "disposal site" for materials which create environmental problems. For example, sulfur is often found in relatively high concentrations in asphalt. Considering these factors, it appears that the asphalts currently being produced have been changing over the last 10 years. However, based on limited research work these changes are not particularly evident as measured by the standard asphalt property tests (1,2). Thus, it appears that more meaningful tests need to be developed and utilized.

Certainly one must accept the opinions offered by these experienced field engineers; however, one must be cautious at the same time. For example, Hveem identified tenderness problems in California in the 1940's (3). Field engineers have complained that asphalt "is not as good as it used to be" as early as the 1930's, and asphalt cracking problems were evident early in the history of asphalt concrete use.

A large number of research projects have been performed to define the original and aged properties of asphalt cements. Numerous asphalt tests have been developed over the years in an attempt to relate laboratory asphalt properties to field performance; however, there has not been a strong correlation between laboratory test parameters and field pavement performance.

Objectives of the Study

The objectives of the study as covered in this report are as follows:

1. To conduct a literature review of the historical changes in asphalt cement properties.
2. To construct three asphalt concrete trial sections in different environments using different asphalt cements.

3. To obtain original asphalt, aged asphalt, recovered asphalt and field performance information over a period of years.
4. To correlate laboratory asphalt properties with field pavement performance.
5. To determine the feasibility of using gel permeation chromatography not only in research but also in quality monitoring.
6. To explore the use of other field and laboratory tests to characterize asphalt cement such as:
   a. Diametral Resilient Modulus Test
   b. Blunt Nosed Penetrometer

Literature Review

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

1. The Asphalt Institute (4)
2. Pennsylvania State University (5,6)
3. FHWA-BPR Studies (7-14)
4. Asphalt Durability Studies (15-17)
5. Asphalt Aging Studies (18-29)
6. Department of Energy (30)
7. Special State Studies (31-39)

In 1977, the Asphalt Institute obtained 211 asphalt cements from 78 refineries and compared the physical properties of these samples to others tested prior to the 1973 oil embargo. Several important observations and conclusions were presented by The Asphalt Institute based on the study (4). These are listed below.

1. Asphalts produced today do not differ substantially from those produced in the past. This appears not only in the conventional properties utilized in material specifications, but also in measurements such as temperature suceptibility, heat effects and shear sensitivity.

2. Asphalts, within a given grade, differ substantially in their properties. However, the magnitude of these differences appears to be similar for asphalts manufactured during different time periods.
3. Both the source of parent oils and the method of refining 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.

There is some disagreement with statement 3. According to Mr. Donald O'Connor of the Texas SDHPT, "all refineries remove the lighter components by vacuum distillation. Some producers use this as the only step to produce paving-grade asphalts. A few producers occasionally air-blow (partially oxidize) slightly soft residues to harden them to the desired consistency. The characteristics of the crude processed by most refineries are such that the heavy ends cannot be reduced to paving-grade asphalt by vacuum distillation. In this case, the heavy oils are removed from the residue by solvent extraction. Normally, propane is the solvent. The asphaltic residue often is harder than paving grade consistency, and some of the extracted oil is added back to produce the various grades."

A study was conducted by Anderson and Dukatz which was particularly relevant to this research. The objective of their research was to determine if there have been changes in the physical or chemical properties of 1980 production asphalts compared to those of 1950 using indicators of potential performance such as fractional composition, temperature susceptibility, effect of heating, and shear susceptibility. Based on their statistical analysis, they concluded that there were changes in the physical and chemical properties of the asphalts sampled over this time period and an increase in temperature susceptibility was also observed. Rostler and Gotolski parameters have also increased in this time period. Rostler parameters were determined to be more closely associated with temperature susceptibility and Gotolski parameters were more closely associated with aging effects.

In the period 1938-39, the Bureau of Public Roads obtained 39 samples of 50-60 penetration and 40 samples of 85-100 penetration asphalt cements (40). Standard physical property tests were performed on these asphalts together with a series of penetration tests from 32 to 140°F at 9°F intervals. From these data, penetration index, penetration ratio and an "exact" penetration temperature susceptibility were calculated in a TTI study (41). By comparing these data from 1938-39 produced asphalts with data from 1954 to 1978 data it can be shown that the temperature susceptibility of asphalt cements has increased with time.

In 1969, Santucci and Schmidt (15) investigated the asphalt properties that best predict the durability of asphalt pavements in terms of fatigue resistance. Asphalts from widely different crude sources were examined. Fatigue resistance was measured on asphalt concrete specimens under a controlled strain mode of loading.

Good correlations were found between recovered asphalt properties and mixture fatigue resistance. Recovered asphalt penetration, asphalt viscosity (calculated from recovered penetration and softening point), and viscosity measured at a constant shear rate were found to predict mixture fatigue behavior reasonably well.

Laboratory microfilm tests designed to simulate the long-term durability of paving asphalts were also found to be suitable in predicting asphalt mixture fatigue resistance.

In 1963, R.N. Traxler (16) studied the changes in asphalt cements during the preparation, laying and service of bituminous pavements. Thirteen asphalts, employed by the Texas Highway Department in their maintenance program at 13 locations in the State, were used in the study. Data showed a small increase in viscosity during the first 2 weeks of service. However, from then on up to 2 years the hardening of the asphalts proceeds much more rapidly.

Another study by Traxler (17) showed that the amount of hardening of the asphalt during construction and the rate of hardening in service are the primary factors affecting durability of a pavement. Pavements containing asphalts with penetrations in the range normally considered satisfactory but with low ductilities are likely to show poorer service than pavements containing asphalts of the same penetration but with high ductilities. The physical characteristics of the pavement, such as void content and permeability, and the environmental factors were found to greatly affect the hardening rate of the asphaltic binder as well as the degree of oxidation during service.

Another study investigating the durability of asphalt cements was performed by Kemp and Predoehl (42). This asphalt durability study involved the weathering of carefully controlled and fabricated briquettes in four distinctly different field environments for four years. They concluded that a high average air temperature is the most significant factor affecting the rate and amount of asphalt hardening. Voids and aggregate properties were also found to be contributing factors. They made the following recommendations to improve asphalt durability:

"1. Adhere to specification compaction requirements to reduce voids,
2. Use asphalts which are most suited to the quality of the aggregate available,
3. Avoid the use of absorbent aggregate whenever possible in hot areas.
4. Use the softest grade of asphalt consistent with curing and stability constraints, and
5. In the hot areas, protect the asphalt concrete mat from heat, oxygen, and water with a cover such as a reflective chip seal.

Gel permeation chromatography, also referred to as size exclusion chromatography, is a branch of high performance liquid chromatography (HPLC) which separates molecules on the basis of their size. Gel permeation chromatography is relatively new and has been used sparingly in the analysis of asphalt since about 1964 (43-53). Most of these studies used GPC to establish the molecular size distribution of asphalts as a "fingerprint" test. In addition, the early work relied on means of detection much less sophisticated than is currently available. The newer equipment and the advances in technique have given the GPC operator the ability to quickly and accurately distinguish between asphalts.

Altgelt (45) demonstrated the power of GPC by taking three asphalts of widely divergent chemical compositions from different crude sources and fractionating them. This study showed that the molecular weight distribution of the asphaltenes may be a factor in the physical properties of asphalts.

Snyder (47) used two asphalts for a determination of molecular weight distribution using GPC. From an analysis of the resulting chromatograms, he calculated R, the ratio of the molecular weights at 90 to 10 weight percent, as a measure of the molecular weight range of the sample. This parameter appeared to be related to pavement performance, but since only two samples were analyzed, no definite conclusions could be reached.

In 1971, Bynum and Traxler (44) conducted a performance analysis of a number of asphalts using GPC. Chromatograms of the asphalts after 0, 4, 6 and 24 months of service were compared. The results showed that differences in chemical composition as reflected by GPC could be observed. The report noted the need for a test which would quickly determine the chemical compositional changes that occur in asphalts under various environmental conditions. The authors concluded that further investigation into the use of GPC in asphalt analysis was warranted.

The most recent study applying GPC to paving asphalts analysis was performed by Jennings (52) for the Montana State Highway Department. The objective of this study was to define by GPC the best performing asphalt available to Montana. This was done by sampling 39 established roadways representing five penetration classes of asphalt. The roads consisted of pavements of various ages. Asphalt cements of different qualities produced by different refining techniques were also considered. Within each penetration class it was noted that the "best" road has a chromatogram similiar to that of the "best" road from other penetration classes. Using the same standard, a general correlation between performance and type of refinery processing was suggested. Based on this information, a model for a superior asphalt was then proposed for Montana highways. This project, however, attempted to correlate asphalt cement properties directly with field pavement performance without regard to such variables as base and subgrade materials, construction techniques or environment. It is obvious that these variables would play an important role in pavement performance particularly where cracking is the distress observed.

The current need is to provide a means of monitoring consistency and relating chemical makeup and properties of asphalt cements with field performance. It is believed that the GPC tool may be used to accomplish these objectives.

CHAPTER II

MATERIALS AND CONSTRUCTION

Asphalt Cements

In order to evaluate the properties of asphalt cements used in Texas an effort was made to select materials that would represent the wide range of properties. Data on the properties of asphalts used in the state were obtained from the Texas State Department of Highways and Public Transportation (SDHPT) and from information produced by previous laboratory work done at the Texas Transportation Institute (TTI). In addition, results of some chemical testing were included in the decision making process. Essentially, the asphalts selected represented the following properties:

1. High and low temperature susceptibility,
2. High potential for water susceptibility,
3. High and low asphaltene content,
4. High and low resistance to oxidative hardening.

Five asphalt sources were chosen. Two grades from each refinery source, AC-10 and AC-20, making a total of ten asphalt cements, were studied in the laboratory.

Of the ten asphalts, seven were used on the Dickens and Dumas field installations and six at Lufkin. The criteria used for selecting the asphalts for each field section were as follows:

1. At least one asphalt from each source would be included.
2. The paving grade normally used in a given area would be first choice from each refinery.
3. At least two asphalts would be a grade not normally used. For example, if AC-10 was the job asphalt grade, then two AC-20 grade asphalts would be used.

Aggregates

Each project used a crushed aggregate that met the Texas SDHPT Type D hot mixed asphaltic concrete specification. A brief summary of the aggregates used at each location is included.

Dickens Aggregate. The aggregate used at Dickens, Texas was mined near the plant site. The coarse and intermediate size aggregates were composed of a crushed siliceous gravel conglomerate. The fine aggregate was of similar mineralogy. The design gradation was obtained by blending the three different sizes in correct proportions. The project design gradation is shown in Figure 1. Note that this material contains only about 3 percent filler size particles.

Dumas Aggregate. The Dumas aggregate was an absorptive, crushed limestone. It was delivered by truck to the plantsite and stored in three separate stockpiles. The combined gradation used in the hot mixed asphalt concrete is shown in Figure 2.

Lufkin Aggregate. The Lufkin aggregate was delivered by truck and stockpiled in three locations at the plant site. A combination of limestone and iron ore gravel type aggregates plus a field sand were used. The gradation of this blend mixture is shown in Figure 3.

Pavement Test Section Construction

Three sections were constructed in three different districts in Texas in order to evaluate environmental effects and construction philosophies. The location of the three sections are shown in Figure 4 and described in Table 1.

In order to evaluate the materials placed at each location, it is imperative that construction information be recorded. Therefore, pertinent data were gathered on each job relating to construction practices. The information obtained for each location is reported.

Dickens, Texas Location. The project was located to the East of Dickens, Texas on U.S. 82 where the mixtures under study were placed in the westbound travel lane. The test sections were placed only after

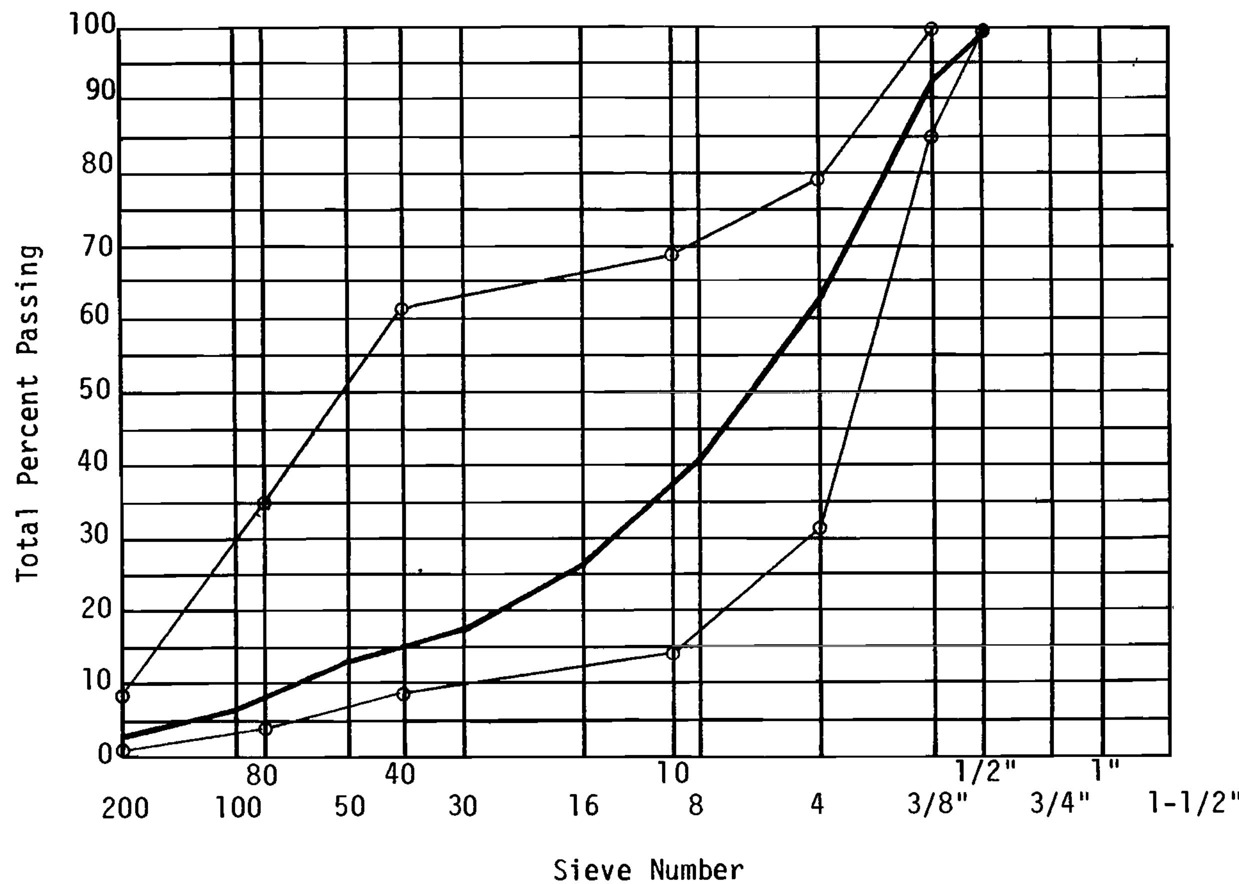

Figure 1. Aggregate Gradation Curve for Dickens, Texas, Asphaltic Concrete Hot Mixture with Texas SDHPT Specification.

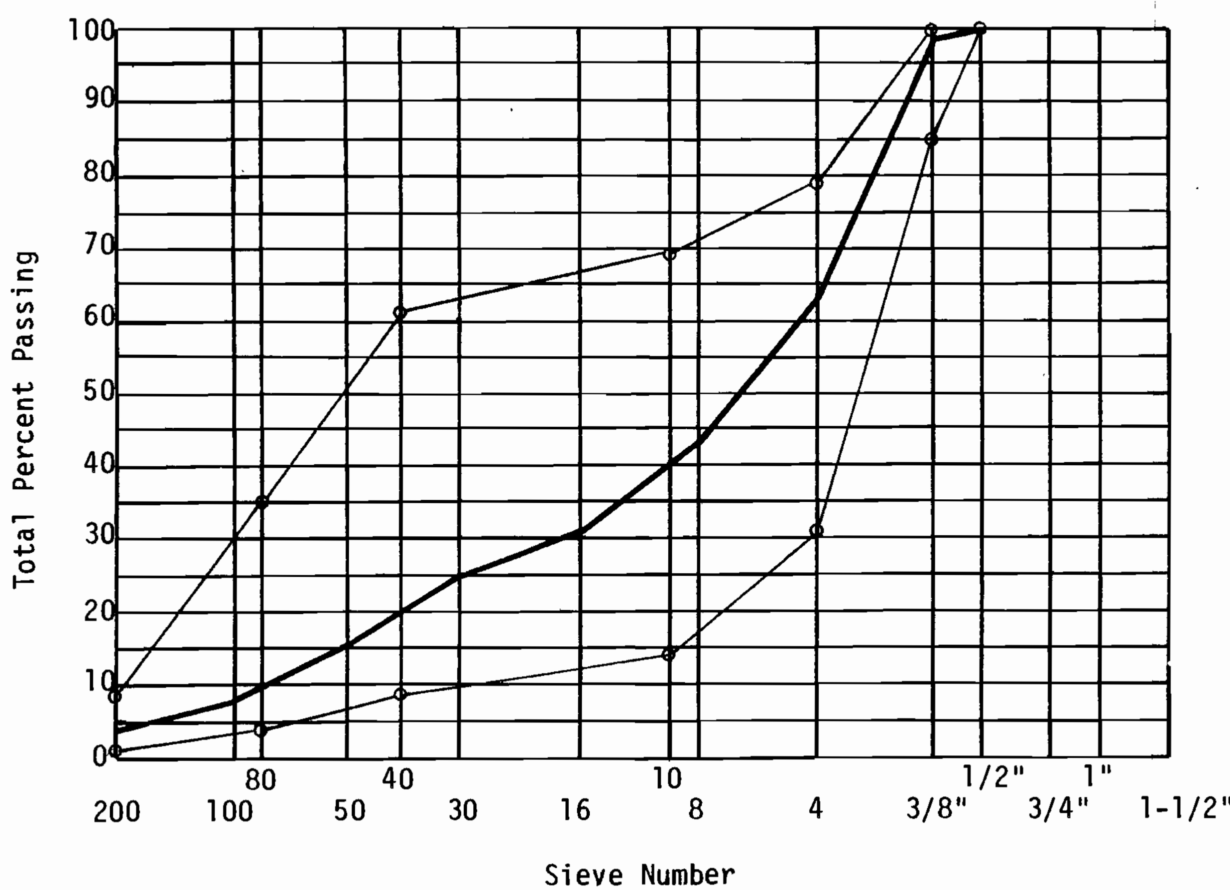

Figure 2. Aggregate Gradation Curve for Dumas, Texas, Asphaltic Concrete Hot Mixture with Texas SDHPT Specification.

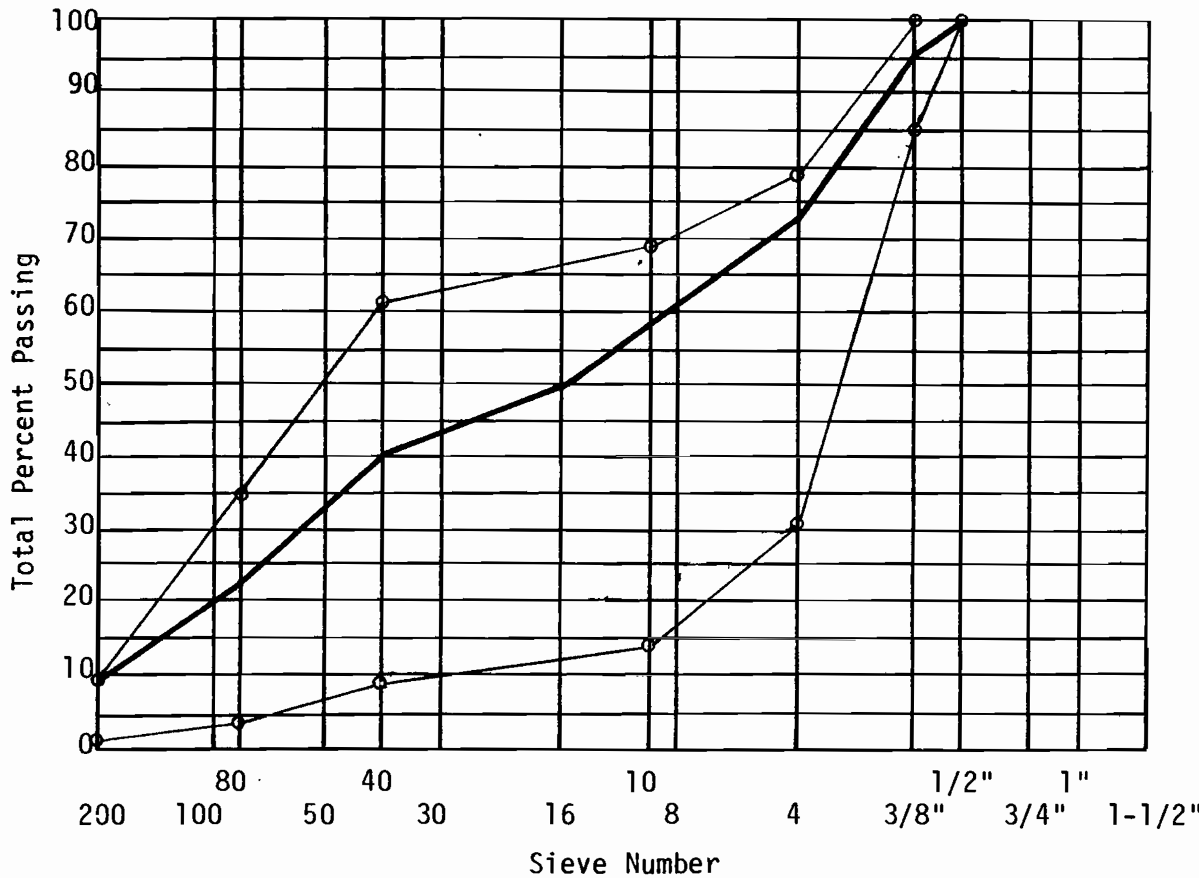

Figure 3. Aggregate Gradation Curve for Lufkin, Texas, Asphaltic Concrete Hot Mixture with Texas SDHPT Specification.

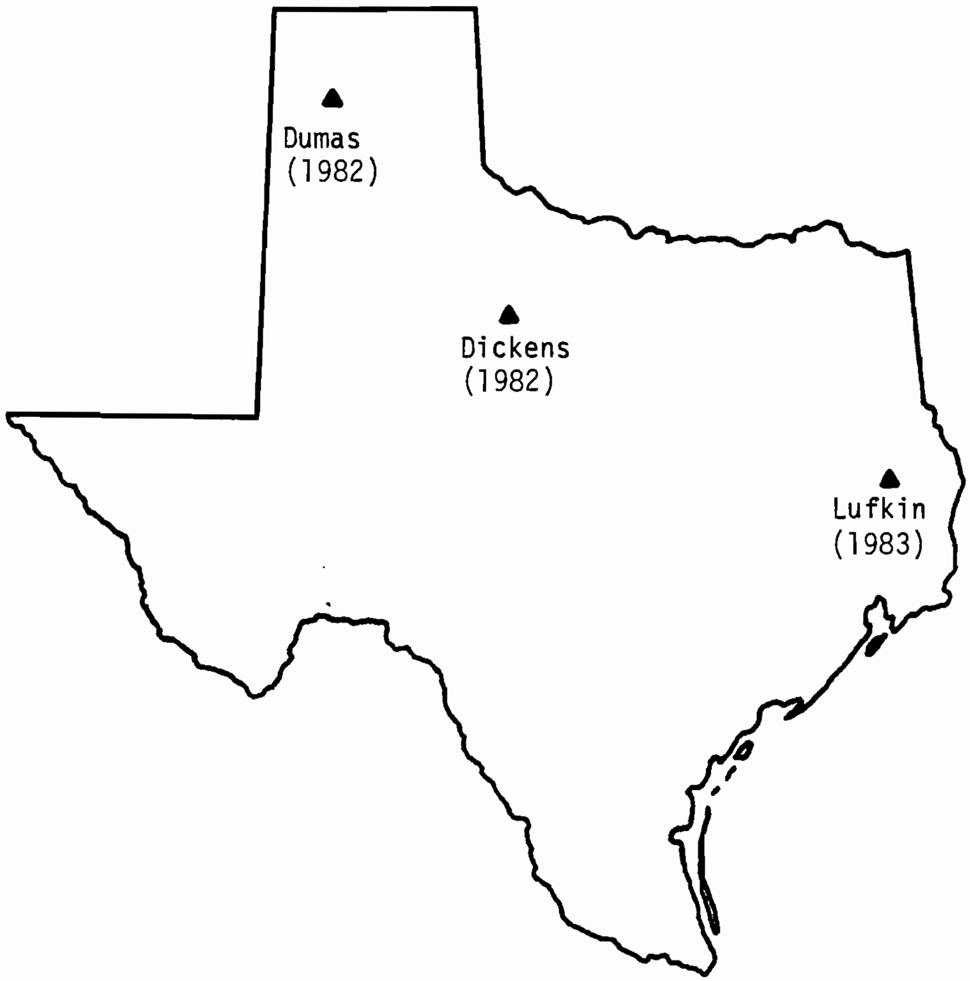

Figure 4. Location of Asphalt Cement Test Sections.

Table 1. Asphalts Used at the Three Field Locations.

Dickens - US 82 West Bound Lane			Dumas - US 287 North Bound Travel Lane			Lufkin - US 96 North Bound Lane	
Asphalt Producer	Asphalt Grade		Asphalt Producer	Asphalt Grade		Asphalt Producer	Asphalt Grade
A	AC-20		A	AC-20		A	AC-20
A	AC-10		A	AC-10		B	AC-10
B	AC-20		B	AC-10		C	AC-20
C	AC-20		C	AC-10		D	AC-20
D	AC-20		D	AC-10		D	AC-10
E	AC-20		E	AC-20		E	AC-20
E	AC-10		E	AC-10			

substantial amounts of mixture had been run through the plant and placed in the passing lane. This meant that asphalt cement from previous mixing plus the test asphalt would be placed in the passing lane. The mixture with the test asphalt cement was then placed in the travel lane. This permitted ample time to convert over to the test asphalt and avoid any contamination of the experimental section.

The plant used was a 1977 Barber-Greene propane fueled dryer drum mixer with a rated capacity of 300 tons per hour. During the first day of operation, production suffered from problems in the plant. Production was so sporadic that operations were stopped until repairs could be made. The problem with the plant was traced to the blower housing of the primary heater and was corrected. From this point on, the plant operated without significant problems.

The first test section was placed without problem, but, toward the end of the construction project, thunderstorms developed and construction was halted for about three days due to wet conditions. Once production was started again, the project was completed without interruption.

The plant was located approximately 20 miles from the construction site. Plant and placement temperature varied as shown in Table 2.

Placement equipment consisted of a Barber Greene laydown machine, a vibratory roller, a small steel wheel roller and pnuematic roller. The vibratory roller was vibrating on its first pass toward the laydown machine and was not vibrating on subsequent passes. Rolling patterns were established by determining the number of passes necessary to achieve maximum density as indicated by a nuclear gauge.

The hot mixed asphaltic concrete was placed on a reconstructed base of well graded aggregate which had been recently treated with a conventional seal coat with Texas SDHPT Grade 3 aggregate.

For the most part, the weather during construction was hot, 90-100^{o}F, and partly cloudy. However, there was some thunderstorm activity at the beginning of the project as previously noted.

The pavement was not opened to traffic for approximatley one week after construction.

Table 2. Mixture Temperatures During Mixing and Placement of the Hot Mixed Asphaltic Concrete at Dickens.

Asphalt Producer	Asphalt Grade	Plant Temperature, °F	Placement Temperature, °F
A	AC-20	285-300	265-290
A	AC-10	280-305	260-290
B	AC-20	265-325	250-280
C	AC-20	270-285	250-275
D	AC-20	275-310	260-300
E	AC-20	280-310	270-280
E	AC-10	275-295	265-295

Dumas, Texas Location. The project was located north of Dumas, Texas on U.S. 287. The experimental sections were placed in the North bound travel lane on a new base sealed with a conventional seal coat utilizing Grade 3 coverstone. Hot mixed asphalt concrete was placed only in the travel lane. "Transition" sections, where the plant was being changed from one asphalt to another, were excluded from the performance evaluation.

The plant used on this project was a Boeing dryer drum plant and produced about 200 tons per hour during the construction of the test sections. The plant had been hit by a tornado a few weeks before the job had started and there was some slight damage to the surge bin. At one point during the construction, insulation fibers were noted at the laydown machine, probably a result of the damage to the surge bin. Also, insufficient coating was observed while the Asphalt C, AC-10 and Asphalt E, AC-10 were being mixed. Several loads of Asphalt C were not accepted at the laydown machine due to this uncoated condition. In general, with the noted exceptions, the plant had no major problems during the production operation.

The test sections were placed from beginning to end without interruption. The entire research portion of the project was completed in three days. Post construction evaluations were performed the following day with the weather having turned cold and rainy.

The plant was located adjacent to the construction site. Plant and placement temperature ranges are shown in Table 3.

The placement and compaction technique was much the same as at the Dickens site. However, the vibratory roller was on the mat much quicker and, therefore, at a somewhat higher temperature.

The weather during construction was cool in the morning, becoming very warm by midday. However, as it has already been pointed out, a front passed through just after the last test section was placed bringing colder weather (about 40^{o}F) and rain.

Since this was a newly constructed pavement, traffic was not allowed on the pavement immediately. It is not known exactly when the sections

Table 3. Mixture Temperatures During the Mixing and Placement of the Hot Mixed Asphaltic Concrete at the Dumas, Texas, Project.

Asphalt Producer	Asphalt Grade	Plant Temperature, °F	Placement Temperature, °F
A	AC-20	295-310	295-305
A	AC-10	300-315	285-300
B	AC-10	300-320	295-305
C	AC-10	295-315	250-315
D	AC-10	295-310	260-280
E	AC-20	300-320	290-310
E	AC-10	305-320	290-315

were opened to traffic, but it was approximately one to two weeks after construction.

Lufkin, Texas Location. In July, 1983, the project was installed approximately 25 miles south of San Augustine, Texas on U.S. 96 extending from the Pineland City limits south to the Jasper County Line. The test pavements were placed end to end in the north bound lane of a two lane highway as an overlay on the old riding surface. The original pavement consisted of a flexible base covered by several surface treatments. Several loads of hot mix were placed before construction of the test pavements was initiated.

The plant was located at Rosevine, Texas, approximately 10 miles from the construction site. The mobile dryer drum plant was manufactured by the CMI Corporation and had a rated capacity of 125 tons per hour. During construction the plant operated at about 70 to 75 percent capacity. There were two asphalt cement holding tanks, the Number 1 tank being 25,000 gallons and the Number 2 tank 12,000 gallons. The Number 2 tank, which is older and has no heating system was used to store the experimental asphalts. To facilitate heating for this tank, a side line pipe was installed from the diesel heating system of the Number 1 tank. Due to this type arrangement, the temperature range in the Number 2 tank varied from 220^{o}F to 250^{o}F. The asphalts were delivered to the site at about 350^{o} F.

Placement and compaction were much the same as the other sites. A vibratory roller stayed close behind the laydown machine followed by a steel wheel roller and a pneumatic finish roller. The plant temperatures ranged from 285^{o}F to 335^{o}F while placement temperatures ranged from 260^{o}F to 310^{o}F.

Weather during construction was a major problem. Construction of the test sections spanned several weeks, causing logistical problems for the research personnel. In fact the first section was placed about four weeks before the last section. Basically, the problem was associated with a period of frequent thunderstorm activity in the area.

Since this project was placed on an existing two-lane facility, it was turned over to traffic at the end of each day.

Chapter III

DESCRIPTION OF EXPERIMENTAL PROGRAM USING STANDARD TEST METHODS

Physical Laboratory Test Program Testing Of Asphalt Cement. Quality control tests currently used in Texas are primarily of a physical nature. Texas SDHPT specifications require the following tests for viscosity graded asphalt cements (54):

Tests on original asphalt:

1. Viscosity at 140°F, stokes
2. Viscosity at 275°F, stokes
3. Penetration at 77°F, dmm (100 grams, 5 seconds)
4. Flash Point, Cleveland Open Cup, degrees F
5. Solubility in trichloroethylene, percent
6. Spot Test

Tests on residues from thin film oven exposure:

7. Viscosity at 140°F, stokes
8. Ductility at 77°F, cm (5 cm per minute)

Appendix A shows the range of acceptable values for each asphalt grade and each test in the Texas Standard Specifications, 1982 (54).

Three specified tests were not performed by TTI. Flash point, solubility in trichloroethlyene, and spot test were performed by the SDHPT and all met the required specifications.

The testing program for the asphalt cements is shown in Figure 5.

Chemical Testing Of Asphalt Cement. The asphalts were sampled from the refineries and the chemical composition was determined using the Rostler-Sternberg (55,56) and Corbett (57) procedures.

Gel permeation chromotography (GPC) was used to define the molecular size distribution of the different components within the asphalts.

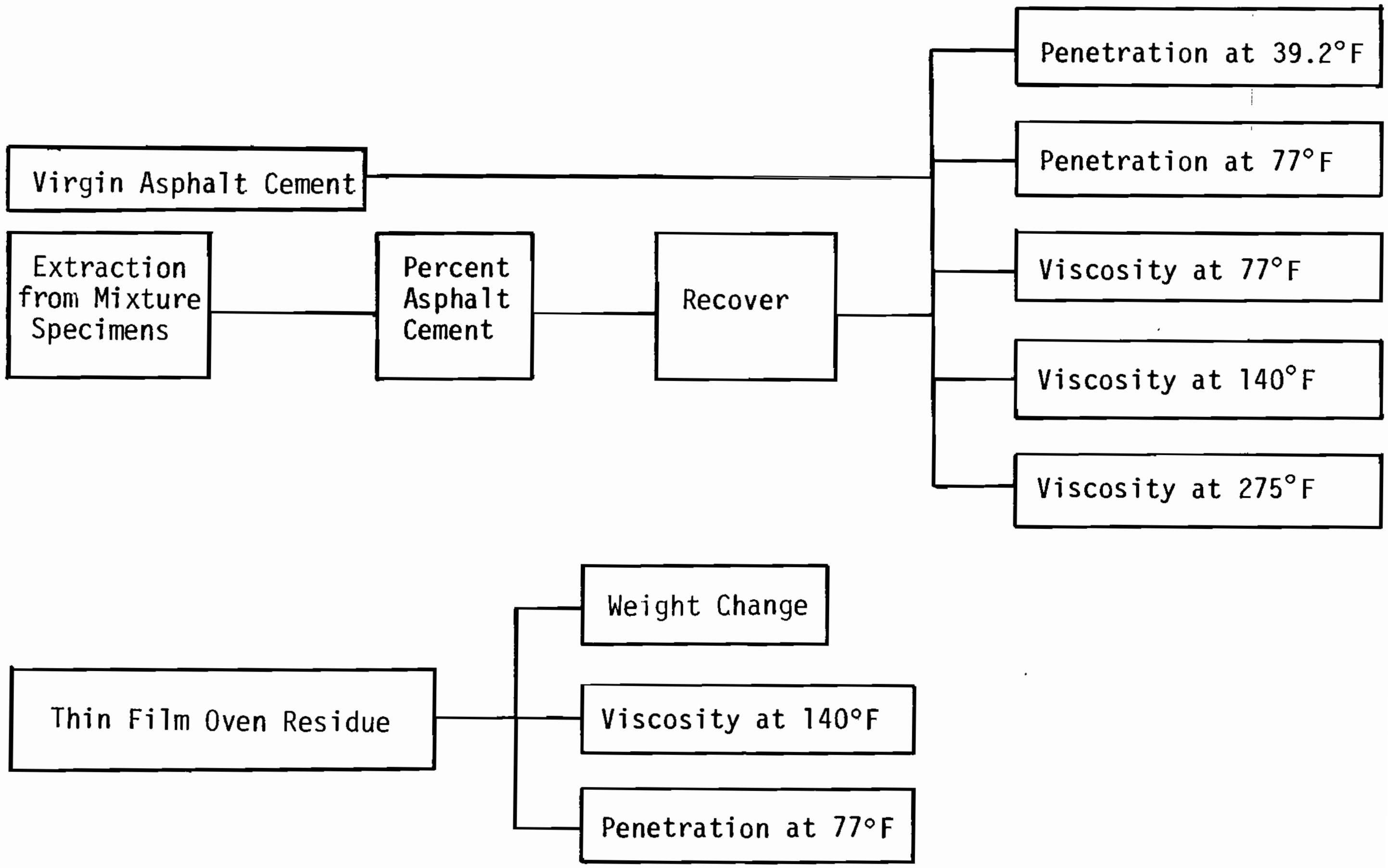

Figure 5. Physical Testing Program for the Asphalt Cements.

Mixture Testing. Tests were performed on the hot mixed asphalt concrete (HMAC) produced at the plant and compacted in both the laboratory and the pavement cores. Loose HMAC containing each asphalt was sampled at each field site. Mixtures were compacted in the laboratory using the standard Texas gyratory method.

The testing program is shown in Figure 6. Resistance to moisture exposure was determined using a modified Lottman (76) procedure. This procedure has one freeze-thaw cycle from $0^{o}F$ to $140^{o}F$.

Test Pavement Performance Evaluation

Performance evaluations of the test pavements were conducted in accordance with Report 151-2 (58) for flexible pavements. Cores taken from every section were tested according to the program shown in Figure 6.

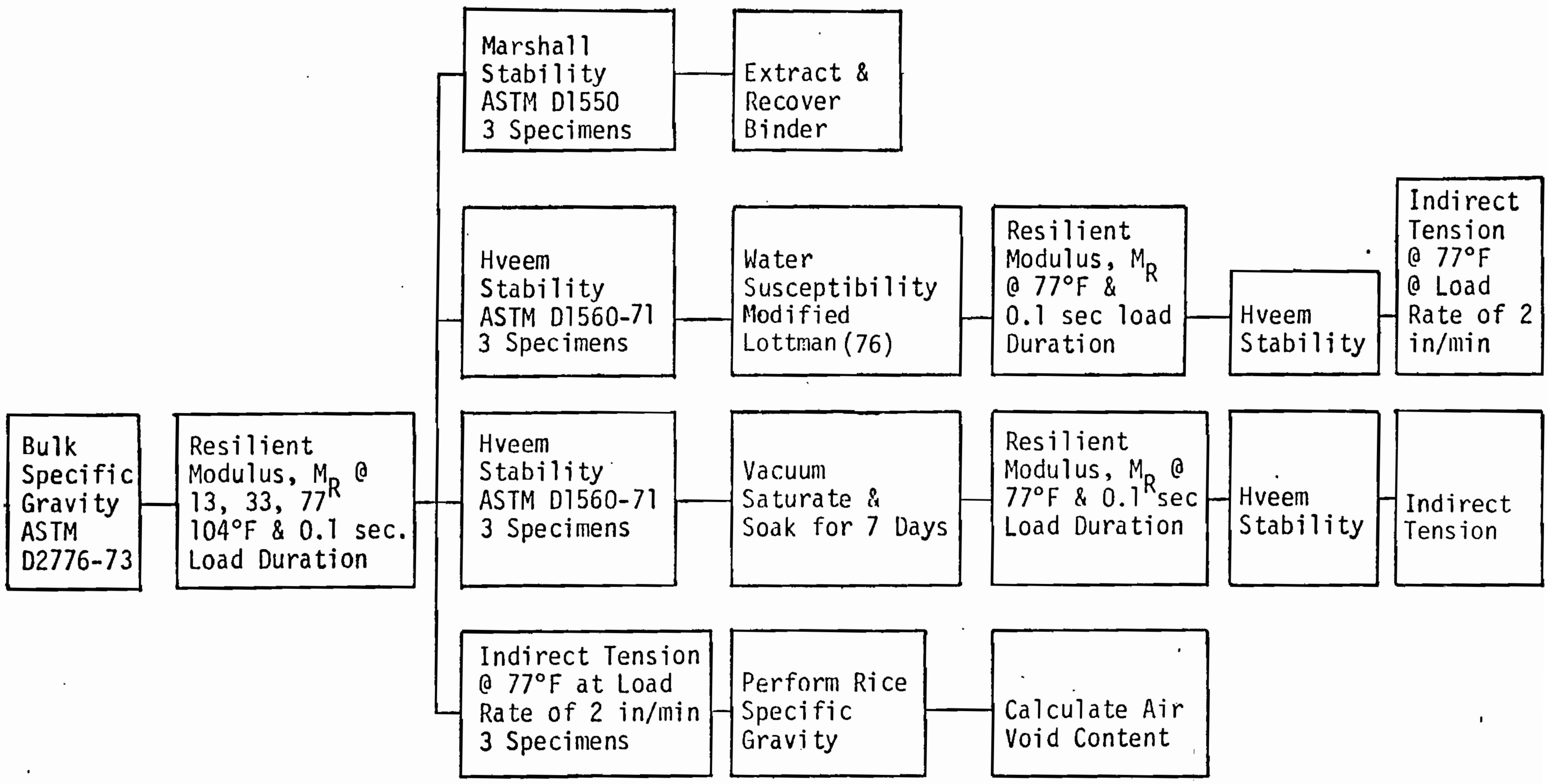

Figure 6. Hot Mixed Asphaltic Concrete Testing Program.

Chapter IV

DESCRIPTION OF EXPERIMENTAL PROGRAM USING NEW TESTS METHODS

The experimental program described herein is concerned with evaluating asphalt properties in concert with field performance to determine those that are the most desirable. In order to achieve this rather ambitious goal, a variety of tests were conducted on the asphalt cements and the asphaltic concrete mixtures. Unfortunately, standard binder tests cannot consistently predict performance of an asphaltic paving mixture. Therefore, new tests and ideas were explored to help identify desirable asphalt properties.

A detailed description of the testing procedures is presented in this chapter.

Gel Permeation Chromatography Testing Program

Gel Permeation Chromatography is a separation on the basis of molecular dimension. The samples were prepared by first dissolving the asphalt in tetrahydrofuran (THF) and then filtering through micro-pore filters. A Waters Associate Model ALC/GPC 202 Liquid Chromatograph equipped with a Model R401 refractometer was used (53). The chromatograms were produced by computer in order to standardize the output for comparison.

The chromatogram shown in Figure 7 represents a typical output from the GPC. The Relative Amount is the refractometer count of molecules in the sample normalized by the computer. Elution time refers to the time required for a particular size molecule to pass through the seperation column. The larger molecules will pass through the column at a faster rate than the smaller molecules and, hence, will be shown first in the chromatogram (Figure 7).

In evaluating the GPC as a test for asphalt cement analysis and quality control, asphalts from each source and grade were tested in their virgin state. Of course only seven asphalts were used at any given field

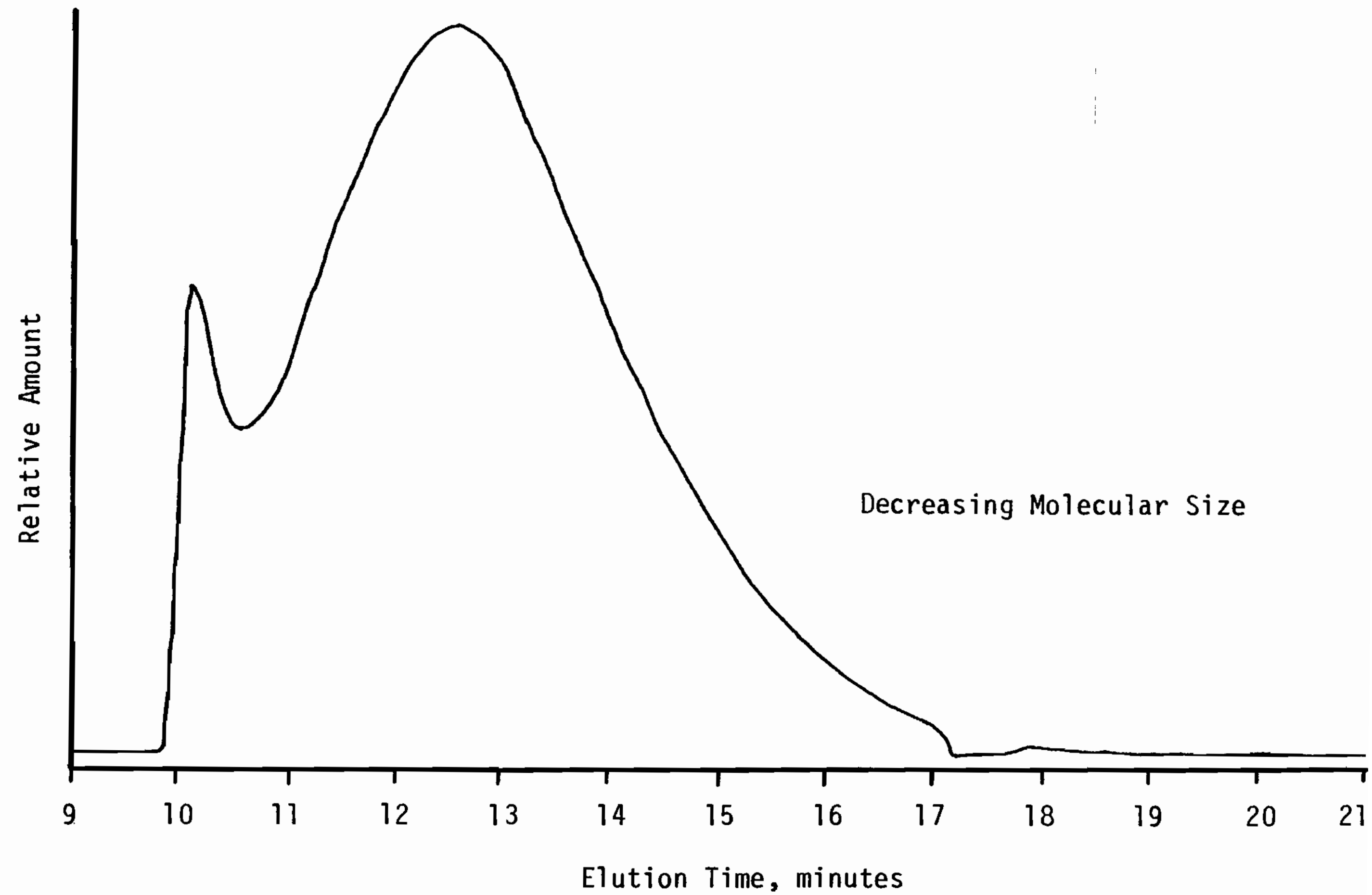

Figure 7. A Typical Chromatogram produced by Gel Permeation Chromatography.

site, but all ten asphalts included in the study were tested as they were received from the refinery. In addition, the asphalts delivered to each site were sampled from the transport, analyzed by the GPC, and compared to the samples sent directly from the refinery at an earlier date.

Generally, GPC provides very repeatable results. This was verified by triplicate tests on two asphalts. It is important to point out that to maintain repeatability the same column or columns with identical packing must be used (59).

GPC tests of asphalts taken from field mixed, laboratory compacted specimens were conducted on a very limited basis to evaluate the potential of the GPC as an analytical test. It was important to see the difference, if any could be observed, in the asphalt cements after having been subjected to the temperatures and chemicals associated with mixing.

Dissipation of Strain Energy in Asphalt Concrete (60)

The indirect tension test has historically been used for the determination of stress, strain and modulus at failure of asphalt concrete. Work by Little and Richey (61) advocates use of a strain energy density (SED), which may also be derived from indirect tension data. SED is defined as the area under the stress-strain curve and represents the amount of energy required to fail a sample (Figure 8). Little points out that SED increases as the binder content in a mix approaches optimum.

For judging the durability of asphalt concrete, SED is an excellent tool. The reasoning behind this statement can be traced to the study of fracture mechanics.

Without an extended discussion of theory, consider the Equation 3.1:

$$\sigma_f = \frac{E\ S}{a} \qquad (3.1)$$

where σ_f = failure stress

S = surface energy of material,

E = modulus of elasticity and

a = 1/2 crack length.

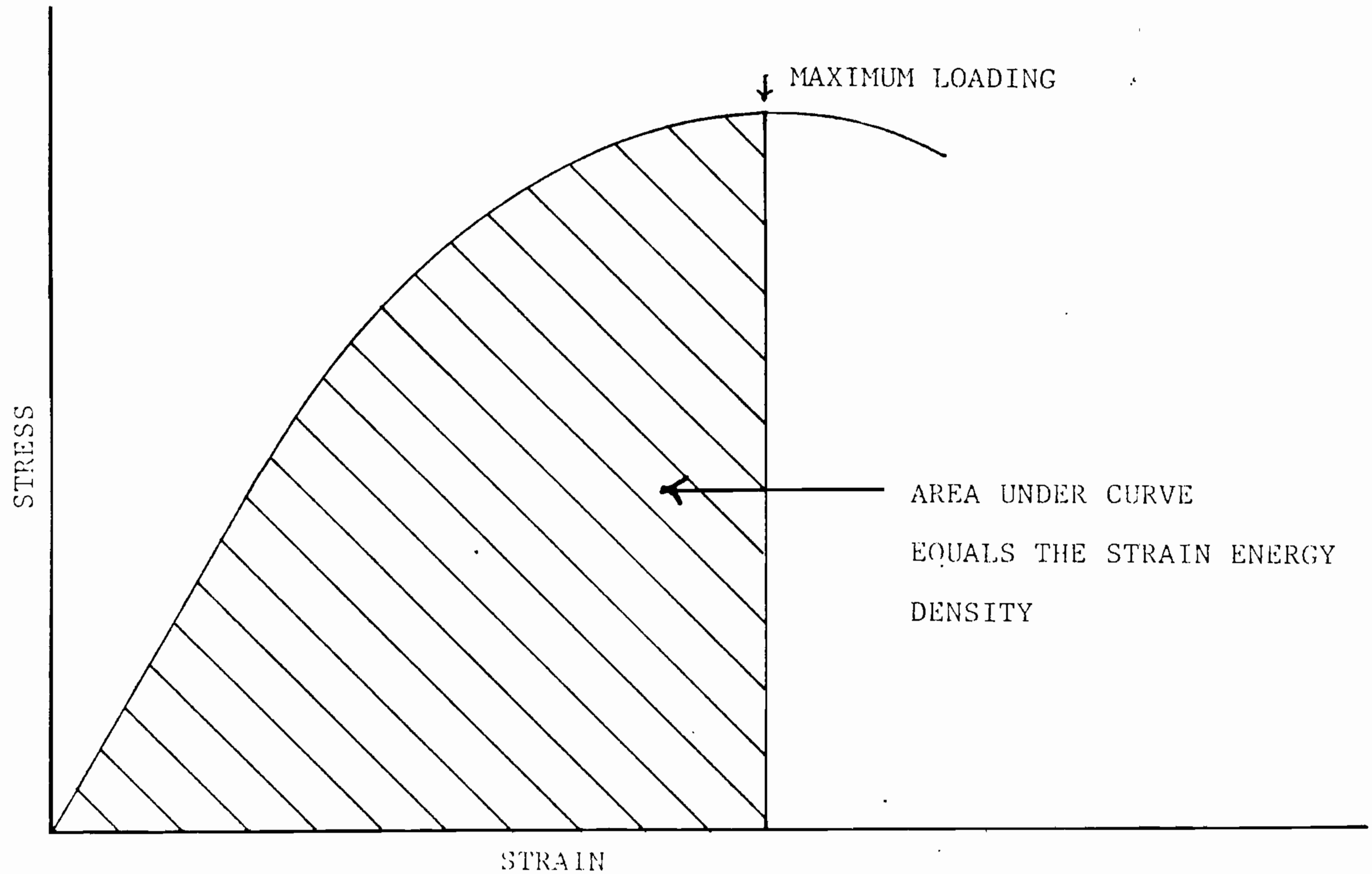

Figure 8. Illustration of Strain Energy Density.

This equation was developed by Griffith. It defines the expected failure stress ($_f$) of a perfectly elastic material containing a crack 2a in length. Work by Orowan employing this relationship (63) yielded unacceptably high values of the surface energy S for metals. He, therefore, replaced the term S with a new term, J; the characteristic energy.

The characteristic energy provides a measure of energy lost in the plastic strain of the sample near the crack tip, which cannot be accounted for in a linear elastic approach. The more energy dissipated by this action, the greater the stress required to propagate cracks in the material.

Work by Rivlin and Thomas (64) promoted the use of the SED directly as a measure of the energy required for crack propagation. Rivlin and Thomas do not base their work on elastic theory, but rather on the energy balance shown in Equation 3.2.

$$- \frac{\alpha E}{\alpha A} , \geq J \qquad (3.2)$$

where $\frac{\alpha E}{\alpha A}$ is the change in energy with respect to the change in the surface area of the crack and

J is the characteristic energy.

Regardless of the approach to the problem, the result is a characteristic energy, J, which is required to propagate the crack through the material. Examining the term J, one finds three primary components: 1. Energy required to fracture the primary covalent bonds, 2. Energy required to overcome Van der Walls forces, and 3. Energy dissipated by the materials (by plastic deformation, etc.) (65).

To the engineer in the field, the existence of a characteristic energy may have no meaning. Bulk properties are much easier to work with. However, by a determination of SED, the engineer can indirectly evaluate the mechanism occurring at the microscopic level.

The preceding discussion is intended only to show, in a conceptual manner the relationship between SED and crack propagation. For a thorough discussion, the reader is referred to the literature (61, 62, 63, 64, 66, 67).

There are three ways in which SED may be used in the diagnosis of asphalt quality: 1. To differentiate among mixtures, 2. To evaluate the sensitivity of mixtures to mixture variables and 3. To measure the effects of aging.

The possibility of using the results of a resilient modulus test to evaluate SED is, therefore of great practical interest. This nondestructive test can closely model loads which the asphalt will encounter in the field. The Mark IV resilient modulus device monitors the rapid changes in stress and strain within asphalt concrete samples. These parameters were monitored for several tests with an oscilloscope. Figures 9, 10, and 11 illustrate the signals generated in the loading of a specimen in the resilient modulus device.

Figure 9 depicts the stress versus time relationship occurring during the test. The stress is generated on the sample in a short amount of time, approximately 0.02 seconds. Once the load peaks, it is held for approximately 0.1 seconds. Finally, the load is released and decays from full load to zero in approximately 0.02 seconds. The small residual stress is due to a spring in the testing device.

Figure 10 shows that, although the sample is given three seconds to recover from the load (30 times the duration of the load) strain still remains in the sample at the initiation of the next load pulse. Presence of the residual deformation causes subsequent hysteresis loops, created by plotting stress versus strain, to be shifted to the right as depicted in Figure 11. The amount of this shift decreases with each cycle for approximately 50 cycles.

To examine this phenomenon more closely it is important to note that ideal elastic material behavior produces no hysteresis loop. Figure 12 illustrates the principle of recovered energy in an elastic material. As the sample is loaded (Figure 12a), energy is introduced into the sample. Upon unloading, energy is released from the sample (Figure 12b). The net

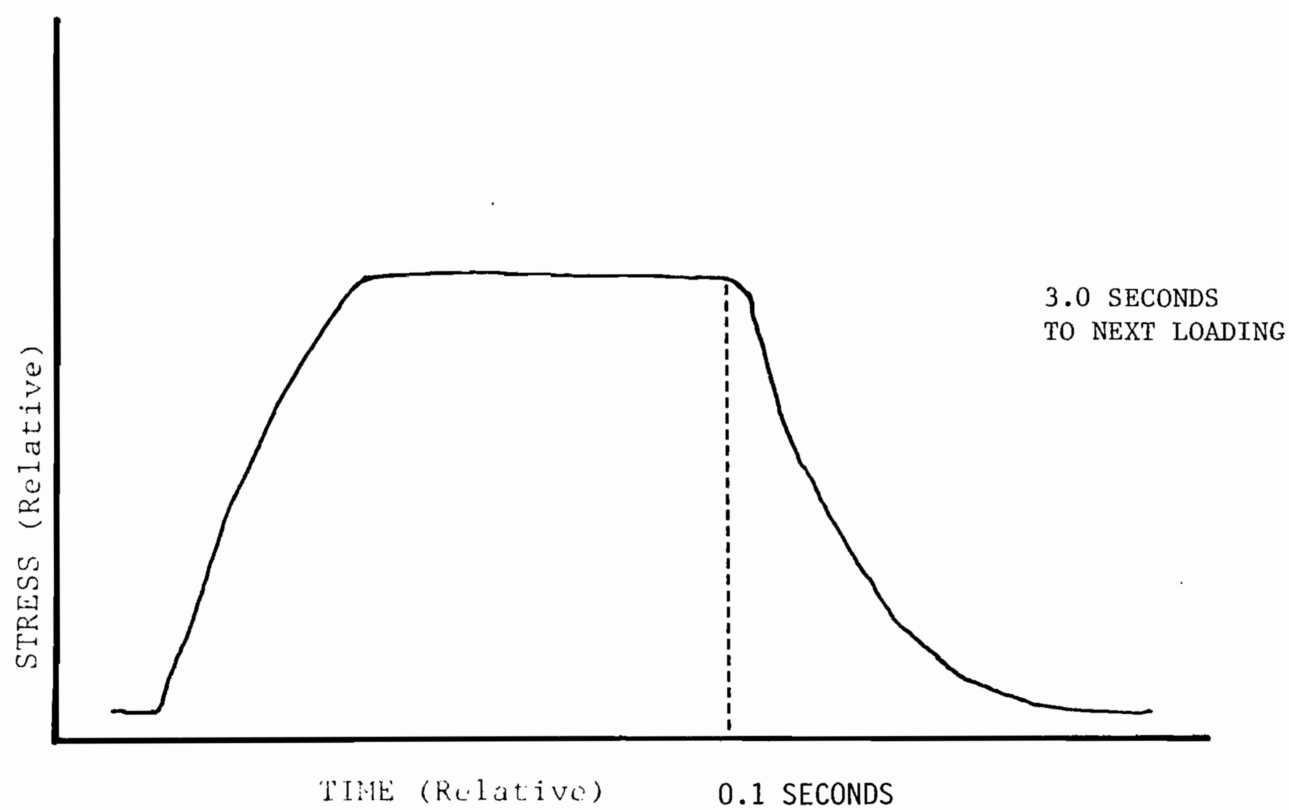

Figure 9. Stress Versus Time Relationship in Resilient Modulus Test.

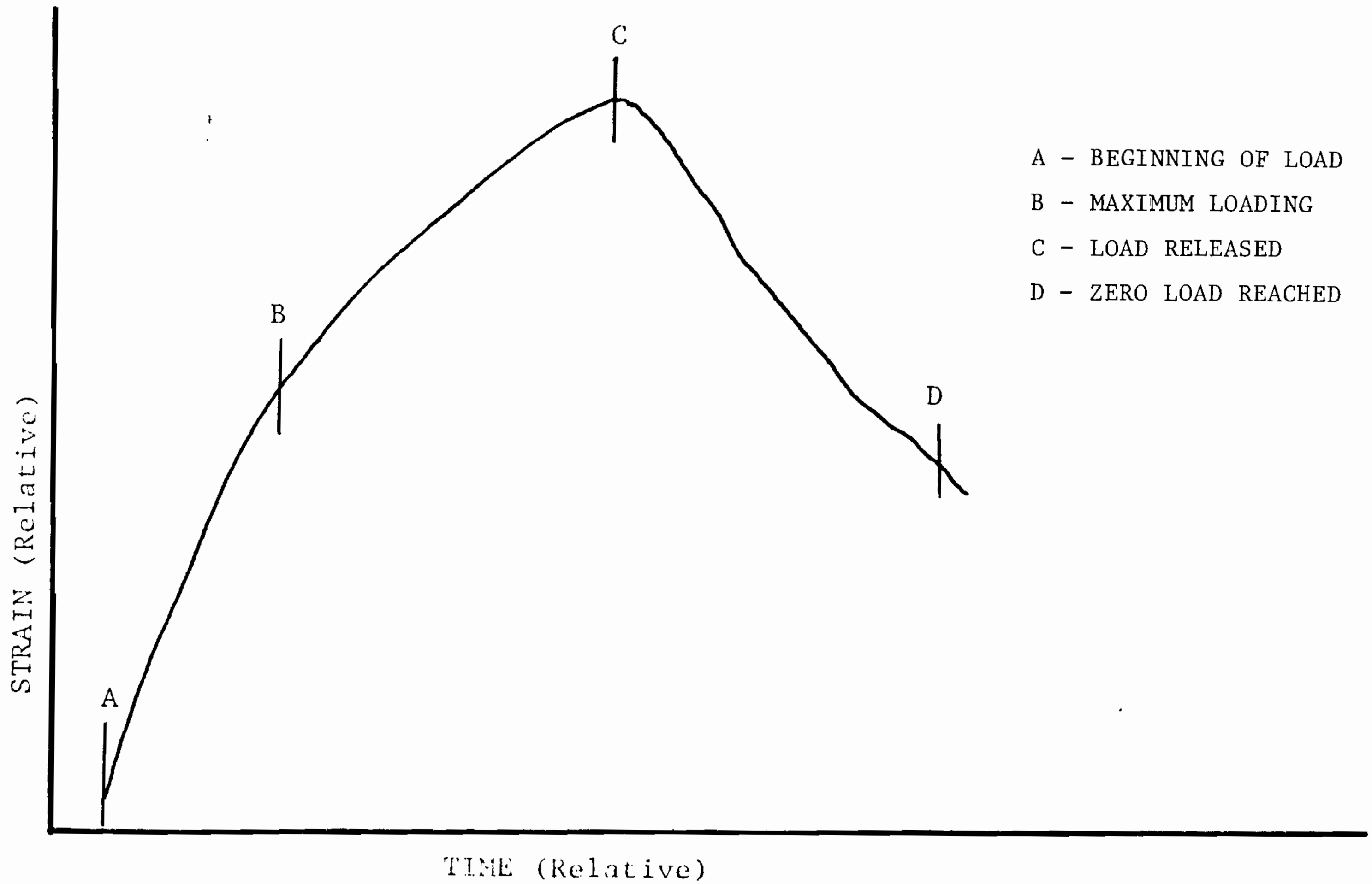

Figure 10. Strain Response in Resilient Modulus Sample.

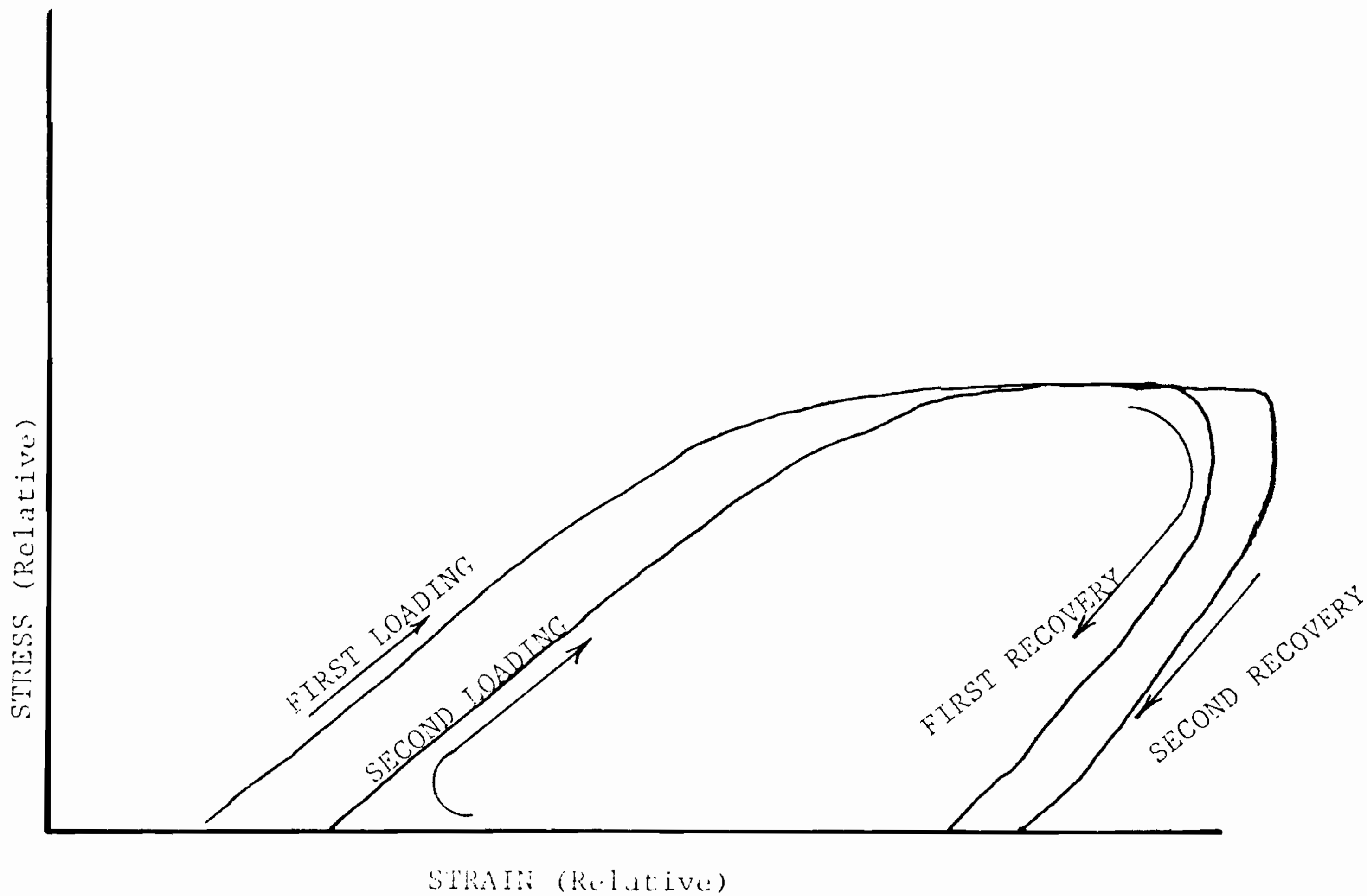

Figure 11. Shift of Hysteresis in Resilient Modulus Test.

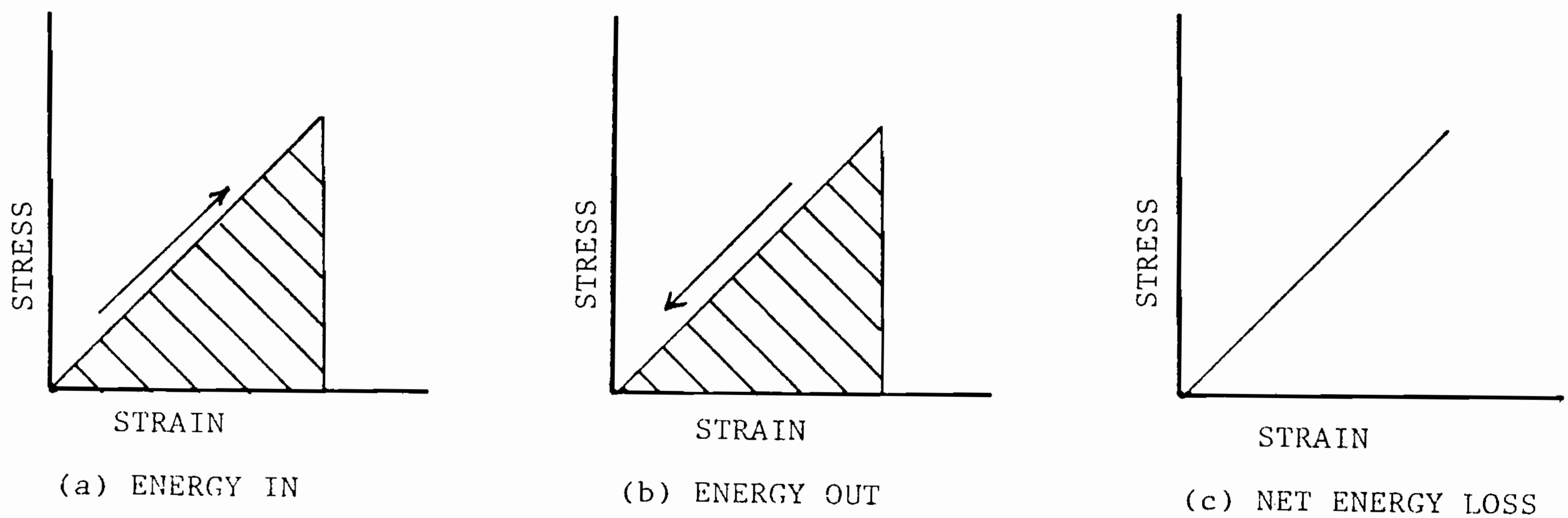

Figure 12. Perfectly Elastic Loading - Unloading Behavior.

absorbed or dissipated energy is then zero (Figure 12c). All energy introduced is stored elastic energy. This is the behavior to be expected of an ideal spring.

Purely plastic materials on the other hand, would show no recovery once the load was removed, yielding a stress-strain relationship like that shown in Figure 13. In this case, all of the energy placed into the system is absorbed by the material (Figure 13 a,b,c). No energy is stored elastically.

Acting as a viscoelastic polymer, however, asphalt both stores and dissipates energy. Figure 14 illustrates the energy which the material is able to dissipate and that which it is not. First, that strain which is elastic is recovered immediately. Second, that strain which is viscous in nature recovers more slowly. Last, a portion of the strain remains as plastic or permanent deformation. The latter two methods of recovery form the visible shifting hysteresis loop. The area enclosed in the hysteresis loop represents the energy which is dissipated within the sample. (62).

A material which undergoes large deformation may be resistant to crack propagation yet unsatisfactory in application as a pavement. This is because excessive plastic deformation is harmful and may result in fatigue as well as permanent deformation. Permanent deformation will manifests itself by ruts, shoving, corrugations, etc. It is desirable then, to differentiate between energy which is dissipated through viscoelastic action from energy which is dissipated through a permanent deformation.

Figure 15 illustrates a methodology for differentiating between the dissipated energy due to viscoelastic effects and those due to permanent deformation. In Figure 15a the energy required to fail a sample may be determined easily from the stress-strain plot. If loading is interrupted, and then resumed, the same energy is required to fail the sample with the exception of an area of overlap. The shaded area in Figure 15b represents the energy which is absorbed by the sample and must be reapplied to bring the sample to the same stress and strain conditions which existed before unloading.

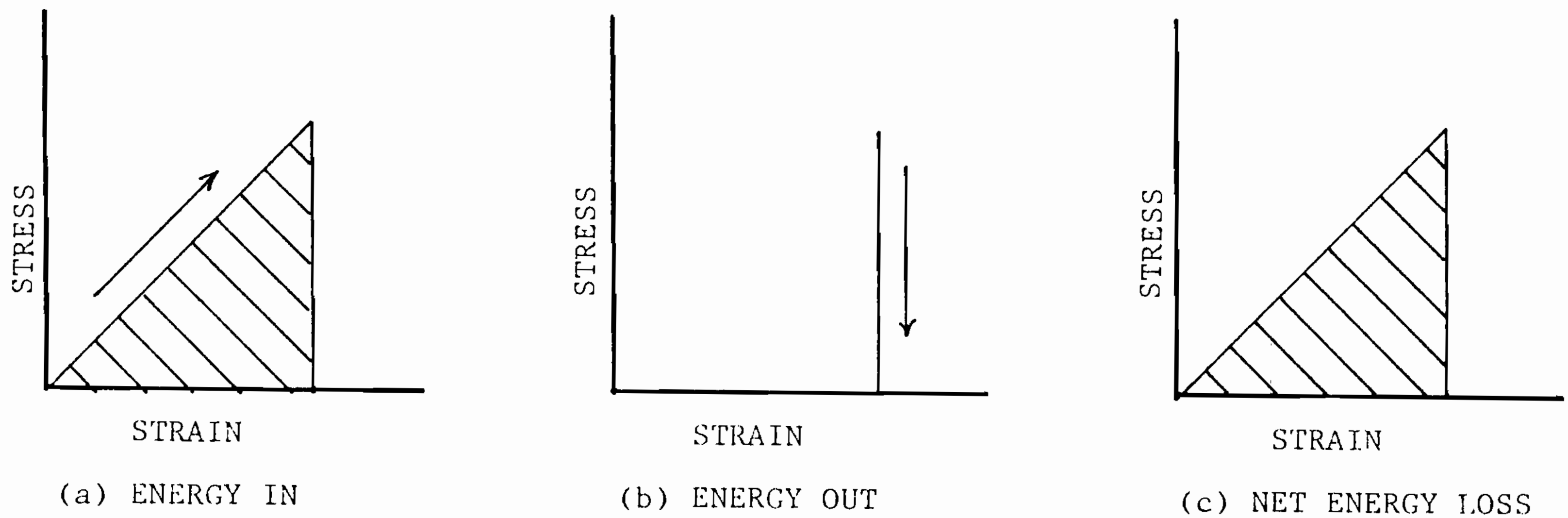

Figure 13. Perfectly Plastic Loading - Unloading Behavior.

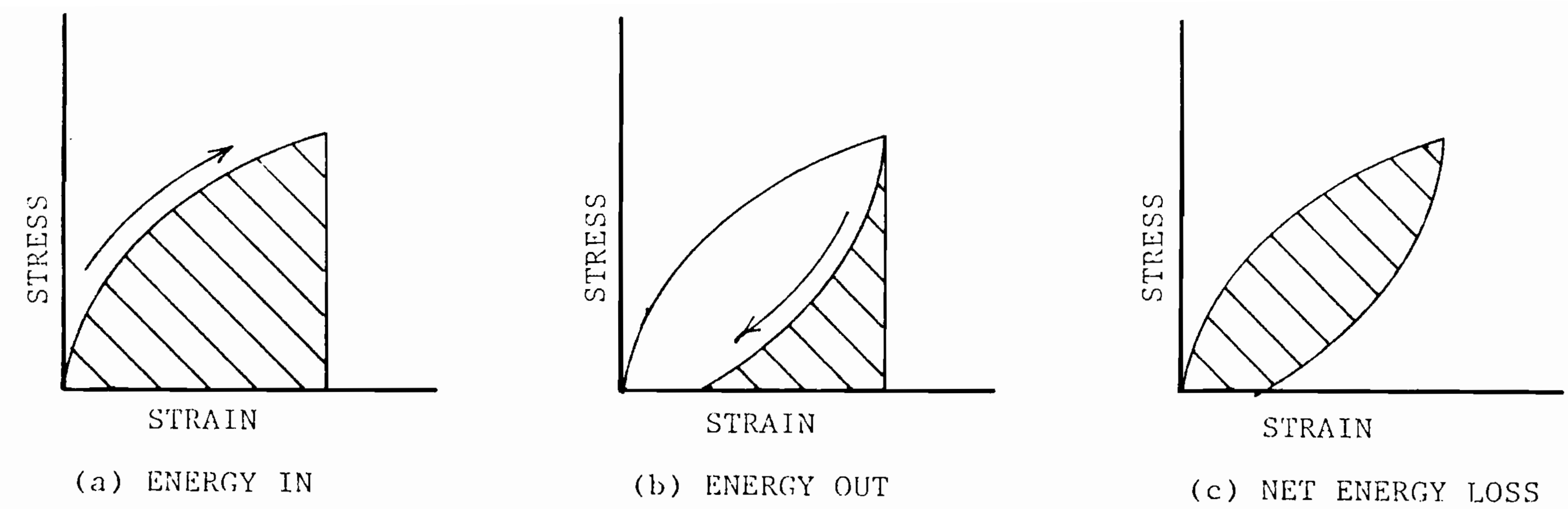

Figure 14. Viscoelastic Loading - Unloading Behavior.

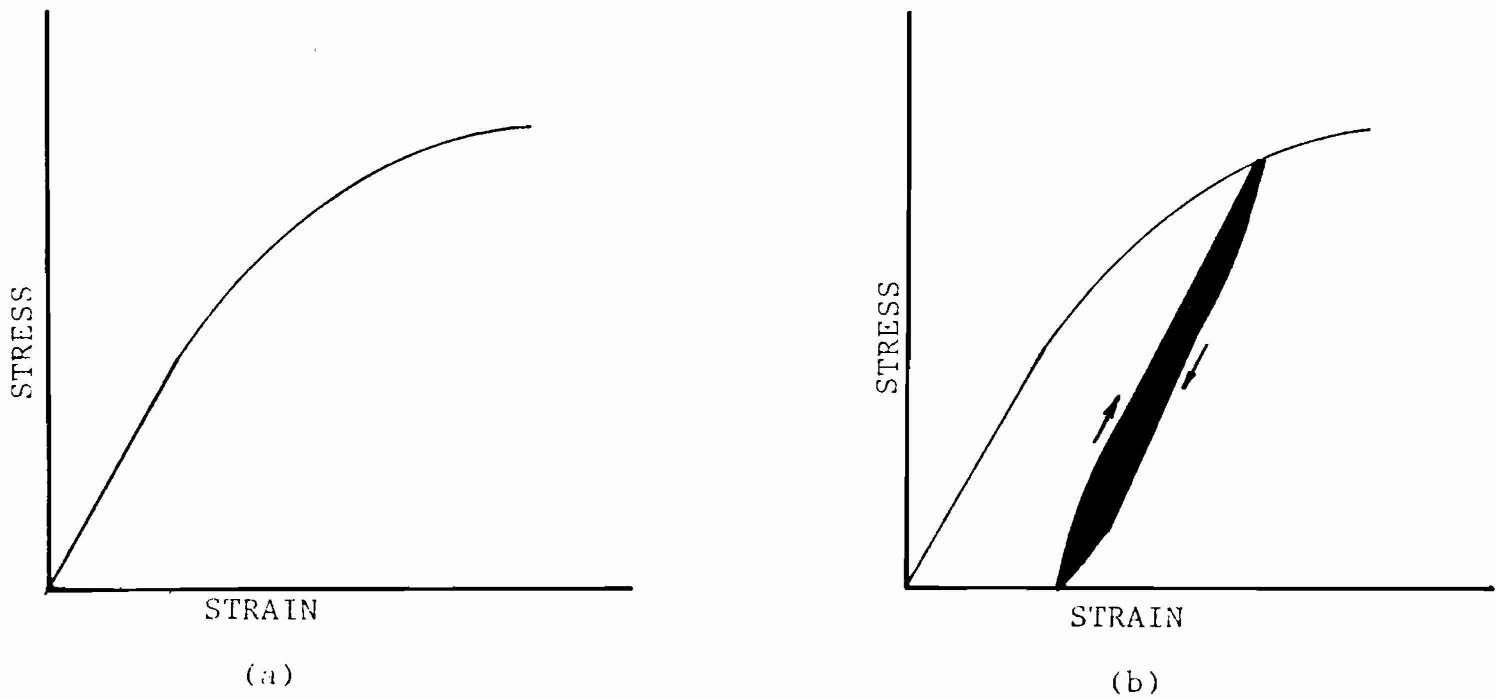

Figure 15. SED With and Without Reloading.

This phenomenon, sometimes referred to as the 'Elastic After Effect' (EAE), is hardly noticeable in crystalline materials, but may be pronounced in polymers (63). The area to the left of the hysteresis loop represents the energy which has been absorbed or dissipated within the material by plastic deformation while that internal to the loop (darkened area) is viscoelastic in nature.

Translating these principles to the hysteresis loop developed in the repeated load resilient modulus test with asphalt concrete, the area internal to the hysteresis loop must represent that energy which the sample dissipated by nonplastic behavior while that to the left of the loop can be recognized as a result of plastic deformation. The assumption that the hysteresis loop represents a viscoelastic response is supported by the fact that the level of applied stress is small (about 10 psi), the recovery period between loadings is comparatively long and the unloading and loading loop retraces itself during cyclic loading and unloading. This effect was carefully monitored on all specimens tested.

Three hundred tests were conducted at 77^{o}F using a Mark IV resilient modulus device. The device was calibrated for the application of a 70-pound repetitive load. All tests were performed at 77^{o}F.

Samples in leg A of Figure 16 were aged in a 140^{o}F room. Samples in leg B were submerged in water at 140^{o}F. Samples were tested as soon as they had cooled, and after 3, 8 and 13 days. Each sample was allowed 24 hours in which to cool to 77^{o}F before testing. Samples in leg B were allowed to drain during the cooling period. Because of the cooling period, samples tested at three days had been aged 48 hours, at 8 days had been aged at 168 hours and at 13 days had been aged 276 hours. Parameters measured were resilient modulus and DSE.

The purpose of the testing was to determine if DSE could differentiate between asphalts of the same physical and chemical classification, but with different chemical and physical properties. The data collected were subjected to an analysis of variance test, specifically the Duncan multiple range test by the Statistical Analysis System (SAS) (68).

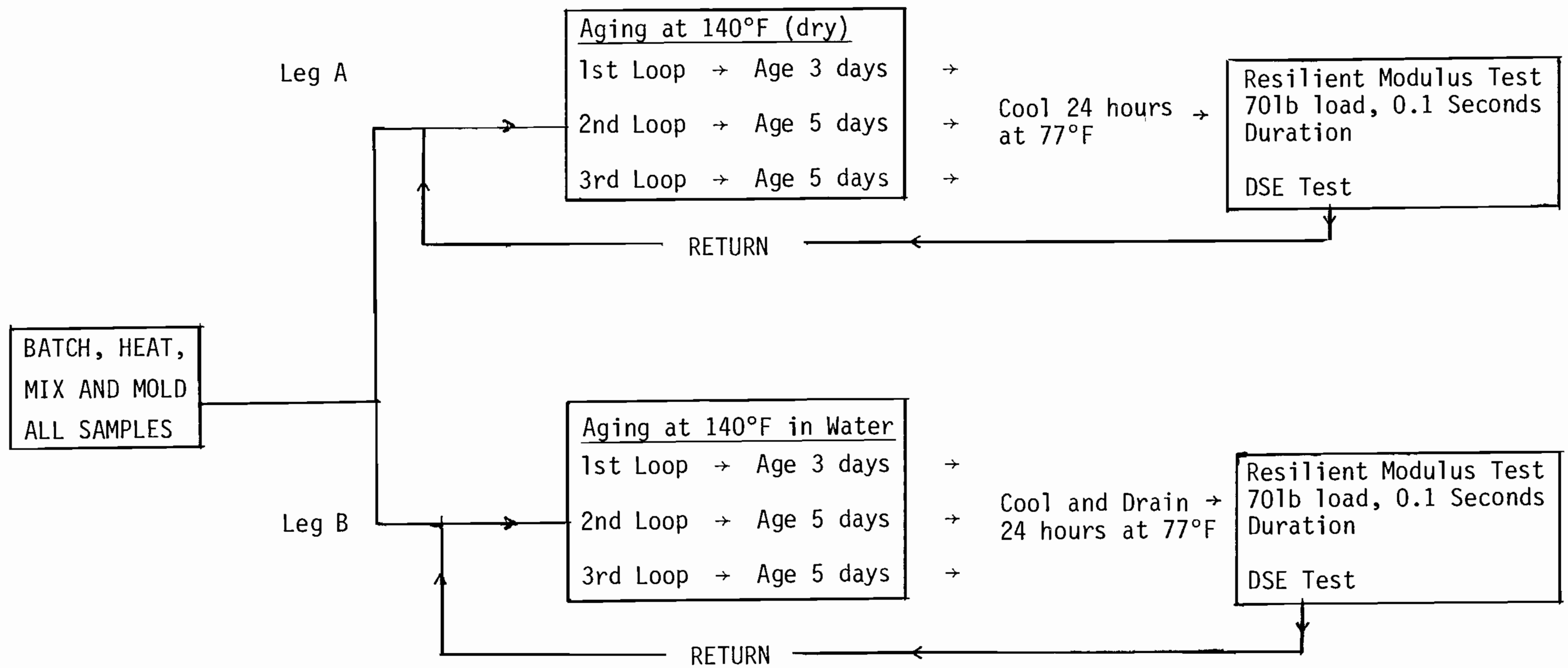

Figure 16. The Testing Program.

If allowed sufficient time to recover (and perhaps with the addition of heat), nearly all permanent deformation in polymers can be recovered (62). It is not possible, therefore, without extensive measurement of recovery between cycles, to determine exactly which portion of the strain imparted to the sample is in fact recoverable.

Measuring the permanent versus recoverable components of the DSE exactly, was found to be unnecessary. The plastic deformation per loading constantly decreases, for 30 to 40 cycles, then the magnitude of the plastic area becomes negligible. To substantiate the insignificance of the plastic portion after several loadings, a special program was developed.

Blunt-Nose Penetration Tests

In 1961, a 1/4-inch diameter blunt-nose penetrometer was developed by Chevron (69) to measure toughness of asphalt concrete mixtures. Most of the original work involved mixtures made with Ottawa sand or other fine-grained aggregates. During the course of a joint NCHRP-SDHPT research project (41), attempts were made to use this device to measure toughness of conventional coarse-grained asphalt concrete mixtures. Scatter in the data was excessive, therefore, attempts were made to modify the penetrometer by increasing the nose diameter and applied load.

Tests using the blunt-nose penetrometer were conducted on the HMAC test sections in Dickens, Texas. Nose diameters of 1/4 inch, 1/2 and 3/4-inch were used with applied loads of 4, 8, 16 and 20 pounds. Approximately 200 tests were conducted in the laboratory and in the field using different variations of nose diameters and applied loads in an attempt to determine what combination would give the most uniform and informative results.

Chapter V

PRESENTATION OF RESULTS FROM STANDARD TEST PROCEDURES

Standard Asphalt Cement Test Results

Chemical composition analyses of the asphalts were performed using the Rostler-Sternberg (55,56) and Corbett (57) procedures. Results are given in Tables 4 and 5, respectively. The results indicate there are wide differences in chemical composition of these asphalts.

Results of the standard physical tests conducted on the asphalt cements are presented in Appendix B. Test results on asphalts sent directly to the laboratory from the producers are shown in Tables B1 and B2. The remainder of Appendix B is arranged such that the virgin asphalt cement tests are presented first followed by extracted asphalts.

The data produced in the physical testing phase have been grouped according to common location. Tables 6 and 7 show the data on the virgin asphalts common to all locations. Figure 17 shows the temperature-viscosity relationship for each virgin asphalt received from the producer. Comparison of the two asphalts shows, it becomes obvious that Asphalt E is more temperature susceptible than Asphalt A. Tables 8 and 9 include data on asphalt cements extracted from field mixtures; these asphalts are common to all locations. Table 8 results are from laboratory compacted samples and Table 9 are results from field cores. Tables 10, 11 and 12 include data on asphalt cements from all locations. Temperature susceptibility of the asphalts was computed using several methods and the results of these computations are listed in Table 13. Asphalt B is generally reputed to be high quality. Generally, Asphalt B also had a lower temperature susceptibility. Asphalt E exhibited the highest temperature susceptibility but is not generally termed as a problem asphalt; its hardening rate was also comparatively high. Asphalt A exhibited a very low asphaltene content and has been associated with slow setting mixtures.

Table 4. **Chemical Composition of Original Asphalts** (Rostler-Sternberg Analysis)

Asphalt Producer	Grade	Rostler-Sternberg Fraction, percent: Pentane Asphaltenes (A)	Nitrogen Bases (N)	1st Acidaffins (A_1)	2nd Acidaffins (A_2)	Paraffins (P)	Rostler Parameter, $\frac{N + A_1}{P + A_2}$	$\frac{N}{P}$
E	AC-10	17	21	21	22	19	1.02	1.11
	AC-20	16	15	24	27	18	0.86	0.83
A	AC-10	5	--*	--	--	--	--	--
	AC-20	4	--*	--	--	--	--	--
C	AC-10	14	20	20	26	20	0.87	1.00
	AC-20	15	20	21	29	15	0.93	1.33
B	AC-10	19	18	16	27	20	0.72	0.90
	AC-20	21	13	16	29	21	0.58	0.62
D	AC-10	20	13	21	27	19	0.74	0.68
	AC-20	24	16	12	28	20	0.58	0.80

*Asphalts from Refinery A typically do not give satisfactory results from the Rostler-Sternberg analysis.

Table 5. Chemical Composition of Original Asphalts (Corbett)

Asphalt Producer	Grade	Corbett Fraction			
		Asphaltenes*	Saturates	Naphthene Aromatics	Polar Aromatics
E	AC-10	11	14	45	30
	AC-20	12	10	43	35
A	AC-10	2	6	49	43
	AC-20	2	2	52	44
C	AC-10	11	9	45	35
	AC-20	11	9	47	33
B	AC-10	10	16	56	18
	AC-20	17	11	47	25
D	AC-10	15	12	47	26
	AC-20	18	9	42	31

*Insoluble in heptane.

Table 6. Physical Properties of Virgin Asphalt Cements Common to All Sites.

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F	140°F	275°F	39.2°F 200g,60 sec	77°F 5g,100s
A	AC-20	Refinery	3.55	2242	6.42	13	61
		Dickens	4.00	2175	7.15	8	65
		Dumas	1.90	2155	6.39	16	61
		Lufkin	1.80	1728	5.05	16	70
E	AC-20	Refinery	2.25	1911	3.10	13	45
		Dickens	1.90	1515	2.87	9	53
		Dumas	1.60	2354	3.17	10	54
		Lufkin	1.90	1858	2.82	10	58

* Viscosity at 77°F given in poises x 10^6, determined using Sliding Plate Viscometer.

Table 7. Physical Properties of the Thin Film Oven Residue of Asphalt Cements Common to All Sites.

Asphalt Producer	Asphalt Grade	Location	Percent Loss	Viscosity, poises 140°F	Penetration, dmm 77°F 100 gm, 5 sec
A	AC-20	Refinery	0	4681	41
		Dickens	0	3536	45
		Dumas	0.02	4344	44
		Lufkin	0.28	4534	46
E	AC-20	Refinery	0.15	4285	32
		Dickens	0.04	5006	27
		Dumas	0.12	4016	32
		Lufkin	0.47	3360	52

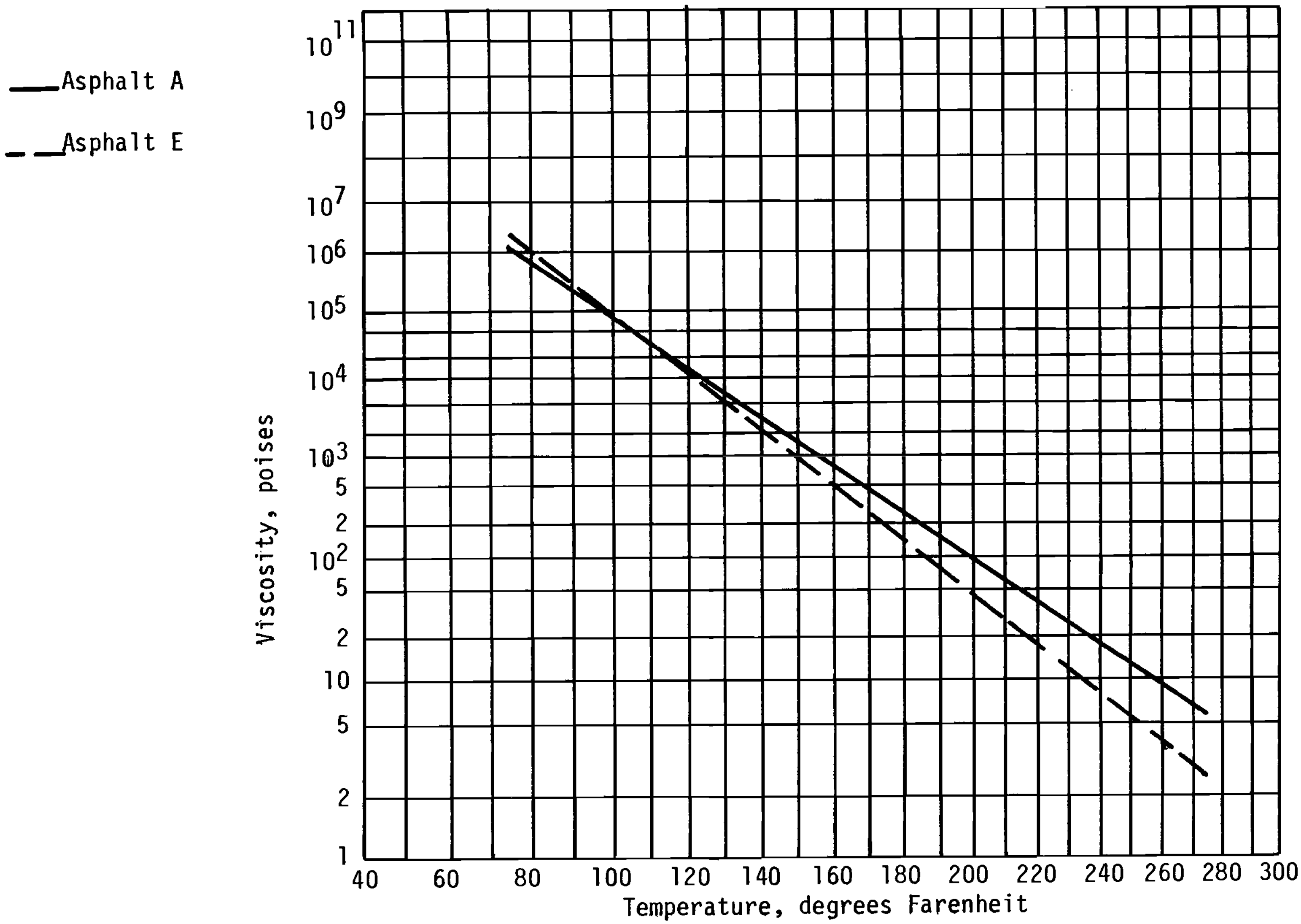

Figure 17. Temperature-Viscosity Relationship for Asphalts A and E, AC-20.

Table 8. Physical Properties of Asphalt Cements Common to All Sites Extracted from Field Mixed, Laboratory Compacted Mixtures.

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F* poises X10^6	140°F	275°F	39.2°F 200gm, 60s	77°F 100, 5s
A	AC-20	Dickens	18.4	9564	11.03	14	29
		Dumas	3.4	2984	7.13	12	51
		Lufkin	4.5	3781	7.45	15	52
E	AC-20	Dickens	14.0	4750	4.49	9	29
		Dumas	5.0	2374	3.42	12	41
		Lufkin	9.0	4307	4.25	4	28

*Viscosity at 77°F was determined using Sliding Plate Viscometer.

Table 9. Physical Properties of Asphalt Cements Common to All Sites Extracted from Cores after One Year Service.

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F * poises $X10^6$	140°F	275°F	39.2°F 200gm,60s	77°F 100g, 5s
A	AC-20	Dickens	12.0	12300	11.76	5	25
		Dumas	5.8	4468	8.41	10	41
		Lufkin	12.1	5553	4.82	0	20
E	AC-20	Dickens	30.0	15466	7.45	0	18
		Dumas	4.6	2453	5.80	8	43
		Lufkin	7.1	5190	6.34	9	38

*Viscosity at 77°F determined using Sliding Plate Viscometer.

Table 10. Physical Properties of Virgin Asphalt Cements

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F poises x10^6	140°F	275°F	39.2°F 200gm, 60s	77°F 100g, 5s
A	AC-10	Refinery	0.66	973	2.76	20	106
		Dickens	1.35	1220	4.51	15	95
		Dumas	0.56	958	4.65	16	104
	AC-20	Refinery	3.55	2242	6.42	13	61
		Dickens	4.00	2175	7.15	8	65
		Dumas	1.90	2155	6.39	16	61
		Lufkin	1.80	1728	5.05	16	70
B	AC-10	Refinery	0.22	773	2.76	35	166
		Dumas	0.36	961	3.63	39	133
		Lufkin	0.76	932	3.63	25	95
	AC-20	Refinery	1.55	3012	5.33	26	64
		Dickens	1.20	2523	4.64	27	77
C	AC-10	Refinery	0.66	1268	2.85	16	80
		Dumas	0.83	1388	3.06	15	74
	AC-20	Refinery	1.70	2183	3.22	18	58
		Dickens	2.75	2576	3.55	7	43
		Lufkin	1.55	1811	3.19	6	64
D	AC-10	Refinery	0.50	931	3.18	35	113
		Dumas	0.53	1030	3.21	30	105
		Lufkin	0.42	1040	2.88	33	111
	AC-20	Refinery	1.11	1812	4.09	26	81
		Dickens	2.50	2151	4.53	22	69
		Lufkin	0.96	1913	3.96	23	79
E	AC-10	Refinery	0.88	955	2.34	17	80
		Dickens	1.15	1264	2.55	15	72
		Dumas	0.97	1038	2.48	16	71
	AC-20	Refinery	2.25	1911	3.10	13	45
		Dickens	1.90	1515	2.87	9	53
		Dumas	1.60	2354	3.17	10	54
		Lufkin	1.90	1858	2.82	10	58

Table 11. Physical Properties of Asphalt Cement Recovered from Field Mixed, Laboratory Compacted Samples.

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F* poise x10^6	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-10	Dickens	12.0	2000	5.93	21	62
		Dumas	1.6	1723	5.24	20	75
	AC-20	Dickens	18.4	9564	11.03	14	20
		Dumas	3.4	2984	7.13	12	51
		Lufkin	4.5	3781	7.45	15	52
B	AC-10	Dumas	0.56	1360	3.49	57	107
		Lufkin	3.5	3600	5.46	22	57
	AC-20	Dickens	7.0	11250	8.30	20	38
C	AC-10	Dumas	2.9	2995	3.86	7	45
	AC-20	Dickens	16.0	8668	6.06	8	21
		Lufkin	3.3	2939	4.40	9	48
D	AC-10	Dumas	1.5	1989	3.98	26	66
		Lufkin	1.3	1866	3.90	19	73
	AC-20	Dickens	1.4	11355	8.74	21	32
		Lufkin	4.1	5940	5.77	5	45
E	AC-10	Dickens	1.30	4322	4.16	8	28
		Dumas	2.0	1943	3.08	12	47
	AC-20	Dickens	14.0	4750	4.49	9	29
		Dumas	5.0	2374	3.42	12	41
		Lufkin	9.0	4307	4.25	4	28

*Viscosity at 77°F determined using Sliding Plate Viscometer.

Table 12. Physical Properties of Asphalt Cement Recovered from Field Cores after One Year Service.

Asphalt Producer	Asphalt Grade	Location	Viscosity, poises			Penetration, dmm	
			77°F* poise x10[6]	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-10	Dickens	17.0	12439	7.29	15	37
		Dumas	2.0	2263	4.81	15	57
	AC-20	Dickens	12.0	12300	11.76	5	25
		Dumas	5.8	4468	8.41	10	41
		Lufkin	4.8	5553	1.21	0	20
B	AC-10	Dumas	0.7	1453	3.59	30	90
		Lufkin	23.0	8666	6.69	3	20
	AC-20	Dickens	21.0	9787	5.67	3	17
C	AC-10	Dumas	2.1	2477	4.41	15	62
	AC-20	Dickens	8.0	5523	8.08	8	32
		Lufkin	26.0	8970	6.16	0	15
D	AC-10	Dumas	1.3	1930	4.04	26	71
		Lufkin	2.3	1866	3.99	17	68
	AC-20	Dickens	21.0	8670	5.79	2	20
		Lufkin	24.0	8400	6.40	0	19
E	AC-10	Dickens	18.5	23115	9.70	10	21
	AC-20	Dickens	30.0	15466	7.45	0	18
		Lufkin	7.1	5190	6.34	9	38

*Viscosity at 77°F determined using Sliding Plate Viscometer.

Table 13. Temperature Susceptibility of Asphalts

Asphalt Producer	Asphalt Grade	Penetration Ratio	Penetration Index	Pen/Vis No.			
				77°F to 275°F	77°F to 140°F		
		Original	Original	Original	Original	TFOT	RTFOT
E	AC-10	21	-1.09	-1.31	-1.16	-1.14	-1.03
	AC-20	29	-1.84	-1.44	-1.28	-0.97	-0.90
A	AC-10	19	-0.97	-0.71	-0.70	-1.07	-0.97
	AC-20	21	-0.59	-0.09	-0.69	-0.55	-0.80
C	AC-10	20	-1.26	-1.02	-0.86	-0.86	-1.14
	AC-20	31	-0.99	-1.15	-0.79	-1.03	-1.14
B	AC-10	21	-0.38	-0.22	-0.19	-0.24	-0.05
	AC-20	41	-0.19	-0.34	-0.32	-0.11	+0.18
D	AC-10	31	+0.13	-0.47	-0.65	-0.46	-0.50
	AC-20	32	+0.04	-0.47	-0.47	-0.45	-0.23

(Continued)

Table 13. Continued.

Asphalt Producer	Asphalt Grade	Viscosity-Temperature Susceptibility			Temperature of Equal stiffness °F(°C)
		77 to 140°F	140 to 275°F	77 to 275°F	
		Original	Original	Original	Original
E	AC-10	4.21	3.66	3.85	-57 (-50)
	AC-20	4.13	3.70	3.85	-43 (-41)
A	AC-10	4.05	3.52	3.71	-65 (-54)
	AC-20	4.22	3.18	3.55	-58 (-50)
C	AC-10	3.84	3.60	3.69	-57 (-49)
	AC-20	3.90	3.72	3.79	-55 (-48)
B	AC-10	3.67	3.42	3.51	-81 (-63)
	AC-20	3.62	3.44	3.50	-65 (-54)
D	AC-10	3.94	3.38	3.58	-80 (-62)
	AC-20	3.83	3.45	3.58	-72 (-58)

Asphalt Concrete Hot Mixture Test Results

Results of the mixture testing are reported in Appendix C. Tables 14 and 15 show the data for the mixtures made with the asphalt cements common to all locations. Tables 16 and 17 show the data for the other asphalts.

Air Voids. Air void content was measured on each specimen tested. There were considerable differences observed between laboratory compacted and field compacted specimens as illustrated in Figures 18 through 20. The Dickens and Dumas specimens had similar air void contents, while the Lufkin specimens were much lower. Void content of the Dumas and Dickens samples compacted in the laboratory ranged from 4 to 8 percent while the Lufkin samples ranged from, 2 to 4 percent. Assuming the standard Texas mixture design procedure was followed, the laboratory mixed and compacted specimens should contain about 3 percent air voids. It is noteworthy that the air void content of the cores from the Dickens and Dumas projects ranged from 10 to 14 percent while those from Lufkin contained only 2 to 4 percent. Air voids have been proven to have a great effect on mixture and asphalt cement properties. When comparing properties between field locations, the difference in air voids must be considered.

Resilient Modulus. Resilient moduli of the cores and laboratory molded specimens were measured at several temperatures to define "mixture" temperature susceptibility to observe the mixture stiffness at higher temperatures, and to monitor flexibility with pavement age. The resilient modulus test is also recognized as a binder sensitive tests performed on asphalt concrete. Results of these tests are provided in Appendix C and are plotted in Figures 21 through 36. Resilient modulus values at 77^{o}F were plotted before and after vacuum saturation and freeze-thaw (Lottman) (76) procedures. There does not appear to be any consistent difference between asphalt producers. The samples from Lufkin are much less water susceptible than those from Dumas or Dickens which may be attributable to the low air void content of the Lufkin cores.

Table 14. Properties of Field Mixed, Laboratory Compacted Mixtures with Asphalt Cements Common to All Sites.

Asphalt Producer	Asphalt Grade	Location	Air Voids, Percent	Resilient Modulus, psi $X10^6$				Indirect Tension		
				-13°F	33°F	77°F	104°F	Stress psi	Strain in/in	Modulus psi
A	AC-20	Dickens	5.5	2.26	1.76	0.579	0.123	117	0.0069	17,800
		Dumas	6.6	1.93	1.46	0.450	0.138	100	0.0037	27,300
		Lufkin	7.4	1.52	1.16	0.422	0.074	135	0.0033	40,800
E	AC-20	Dickens	6.7	2.16	1.62	0.603	0.130	140	0.0082	17,100
		Dumas	8.6	1.93	1.39	0.561	0.148	140	0.0038	38,200
		Lufkin	3.3	2.17	1.32	0.345	0.071	198	0.0050	39,600

Table 15. Properties of Field Mixed, Field Compacted Mixtures with Asphalt Cements Common to All Sites after One Year Service.

Asphalt Producer	Asphalt Grade	Location	Air Voids, Percent	Resilient Modulus, psi X10^6				Indirect Tension		
				-13°F	33°F	77°F	104°F	Stress psi	Strain in/in	Modulus psi
A	AC-20	Dickens	10.0	1.73	0.970	0.262	0.048	51	0.0060	8,600
		Dumas	11.6	1.73	1.12	0.369	0.086	86	0.0027	32,400
		Lufkin	2.6	2.50	1.28	0.254	0.072	144	0.0033	45,600
E	AC-20	Dickens	11.8	2.53	1.48	0.394	0.056	128	0.0039	56,400
		Dumas	10.5	1.68	1.29	0.388	0.084	93	0.0024	39,700
		Lufkin	3.2	2.60	1.84	0.509	0.082	238	0.0026	93,300

Table 16. Properties of Field Mixed, Laboratory Compacted Mixtures.

Asphalt Producer	Asphalt Grade	Location	Air Voids, Percent	Resilient Modulus, psi x 10^6				Indirect Tension		
				-13°F	33°F	77°F	104°F	Stress, psi	Strain, in/in	Modulus, psi
A	AC-10	Dickens	4.1	2.39	1.59	0.342	0.053	86	0.0100	8,500
		Dumas	5.5	1.81	1.36	0.318	0.072	63	0.0049	12,900
	AC-20	Dickens	5.5	2.27	1.76	0.579	0.123	117	0.0069	17,800
		Dumas	6.6	1.93	1.46	0.450	0.138	100	0.0037	27,300
		Lufkin	7.4	1.52	1.16	0.423	0.074	135	0.0033	40,800
B	AC-10	Dumas	8.5	2.02	1.66	0.285	0.080	73	0.0046	15,700
		Lufkin	2.0	1.59	1.04	0.217	0.062	110	0.0044	25,400
	AC-20	Dickens	5.8	1.88	1.17	0.374	0.100	102	0.0033	31,500
C	AC-10	Dumas	10.7	2.21	1.35	0.416	0.122	104	0.0033	32,500
	AC-20	Dickens	6.3	2.29	1.66	0.666	0.128	159	0.0036	44,400
		Lufkin	4.2	2.06	1.41	0.388	0.107	266	0.0043	64,400
D	AC-10	Dumas	7.5	1.79	1.26	0.318	0.099	86	0.0038	23,000
		Lufkin	3.9	1.75	1.08	0.166	0.047	105	0.0043	25,000
	AC-20	Dickens	4.7	2.24	1.34	0.501	0.117	122	0.0035	35,000
		Lufkin	3.4	1.89	1.09	0.214	0.055	139	0.0043	32,500
E	AC-10	Dickens	5.1	1.97	1.45	0.512	0.092	131	0.0091	14,500
		Dumas	6.1	1.87	1.68	0.519	0.141	126	0.0044	28,800
	AC-20	Dickens	6.7	2.16	1.63	0.603	0.130	140	0.0082	17,100
		Dumas	8.6	1.93	1.39	0.561	0.148	140	0.0038	38,200
		Lufkin	3.3	2.17	1.32	0.349	0.071	198	0.0050	39,700

Table 17. Properties of Field Mixed, Field Compacted Mixtures After One Year Service.

Asphalt Producer	Asphalt Grade	Location	Air Voids, Percent	Resilient Modulus, psi x 10^6 -13°F	33°F	77°F	104°F	Indirect Tension Stress, psi	Strain, in/in	Modulus, psi
A	AC-10	Dickens	14.3	1.30	0.804	0.232	0.076	76	0.0035	22,000
		Dumas	6.2	1.60	0.958	0.151	0.033	75	0.0060	12,500
	AC-20	Dickens	10.0	1.73	0.970	0.262	0.048	51	0.0060	8,600
		Dumas	11.6	1.73	1.12	0.369	0.086	86	0.0027	32,400
		Lufkin	2.6	2.50	1.28	0.254	0.072	144	0.0033	45,600
B	AC-10	Dumas	13.7	1.54	0.811	0.134	0.027	50	0.0038	13,200
		Lufkin	6.2	2.75	2.05	0.654	0.109	245	0.0025	113,500
	AC-20	Dickens	9.9	2.33	1.31	0.345	0.064	107	0.0036	31,100
C	AC-10	Dumas	15.4	1.32	0.918	0.195	0.039	70	0.0038	18,300
	AC-20	Dickens	9.9	2.13	1.20	0.197	0.044	83	0.0056	15,300
		Lufkin	3.0	2.58	1.43	0.204	0.045	158	0.0039	41,100
D	AC-10	Dumas	12.2	1.83	1.05	0.315	0.097	77	0.0025	31,800
		Lufkin	4.2	2.41	1.64	0.499	0.141	189	0.0024	84,900
	AC-20	Dickens	14.1	1.87	1.25	0.318	0.062	94	0.0033	28,800
		Lufkin	2.2	2.24	1.26	0.165	0.040	116	0.0051	25,200
E	AC-10	Dickens	14.5	1.47	0.686	0.144	0.034	54	0.0438	1,270
		Dumas	13.8	1.77	1.23	0.440	0.087	107	0.0025	42,700
	AC-20	Dickens	12.3	1.63	1.30	0.510	0.203	142	0.0022	64,600
		Dumas	10.5	1.68	1.29	0.388	0.084	93	0.0024	39,700
		Lufkin	3.2	2.60	1.84	0.509	0.082	238	0.0026	93,300

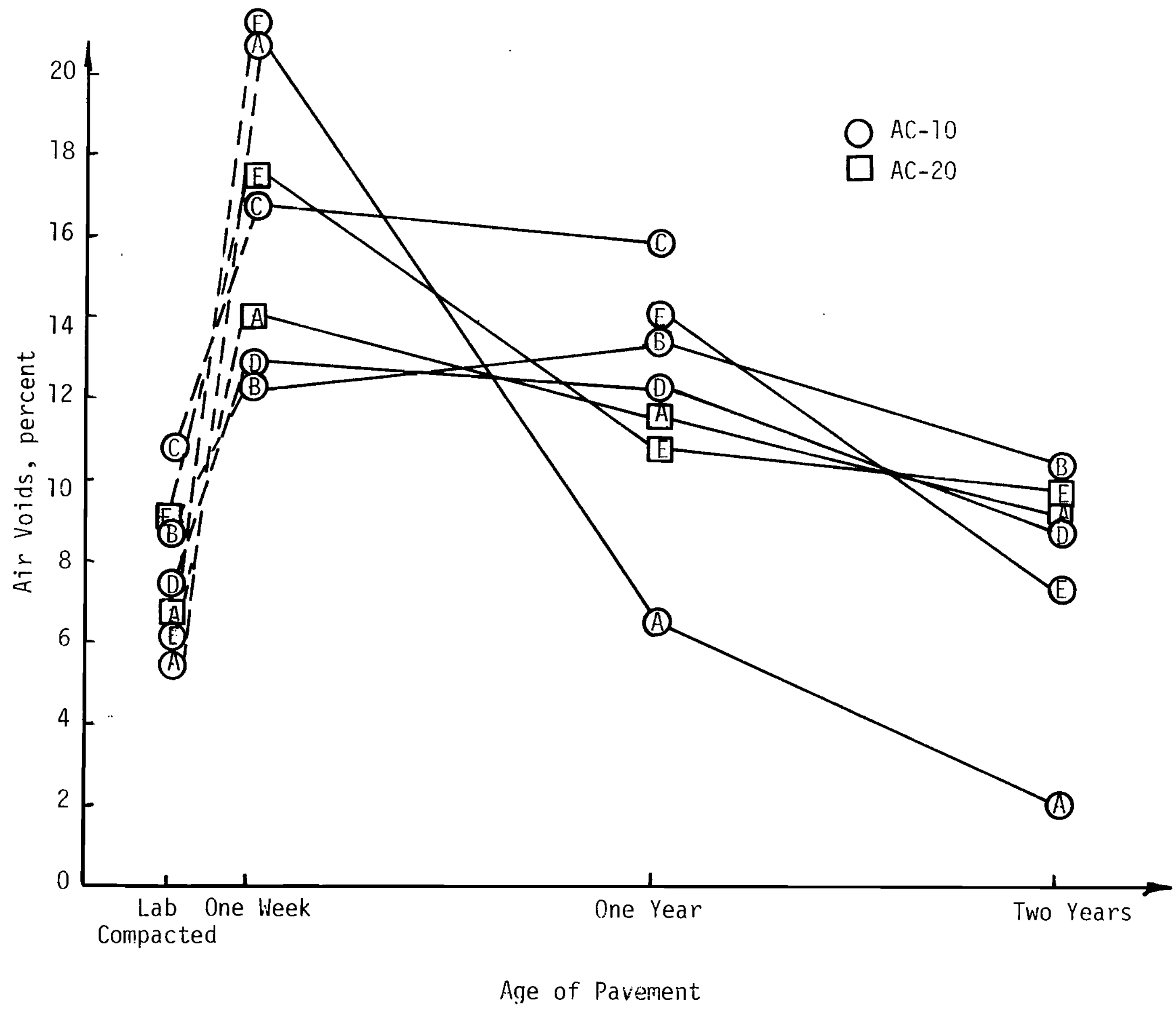

Figure 18. Percent Air Voids versus Pavement Age for Dumas Cores.

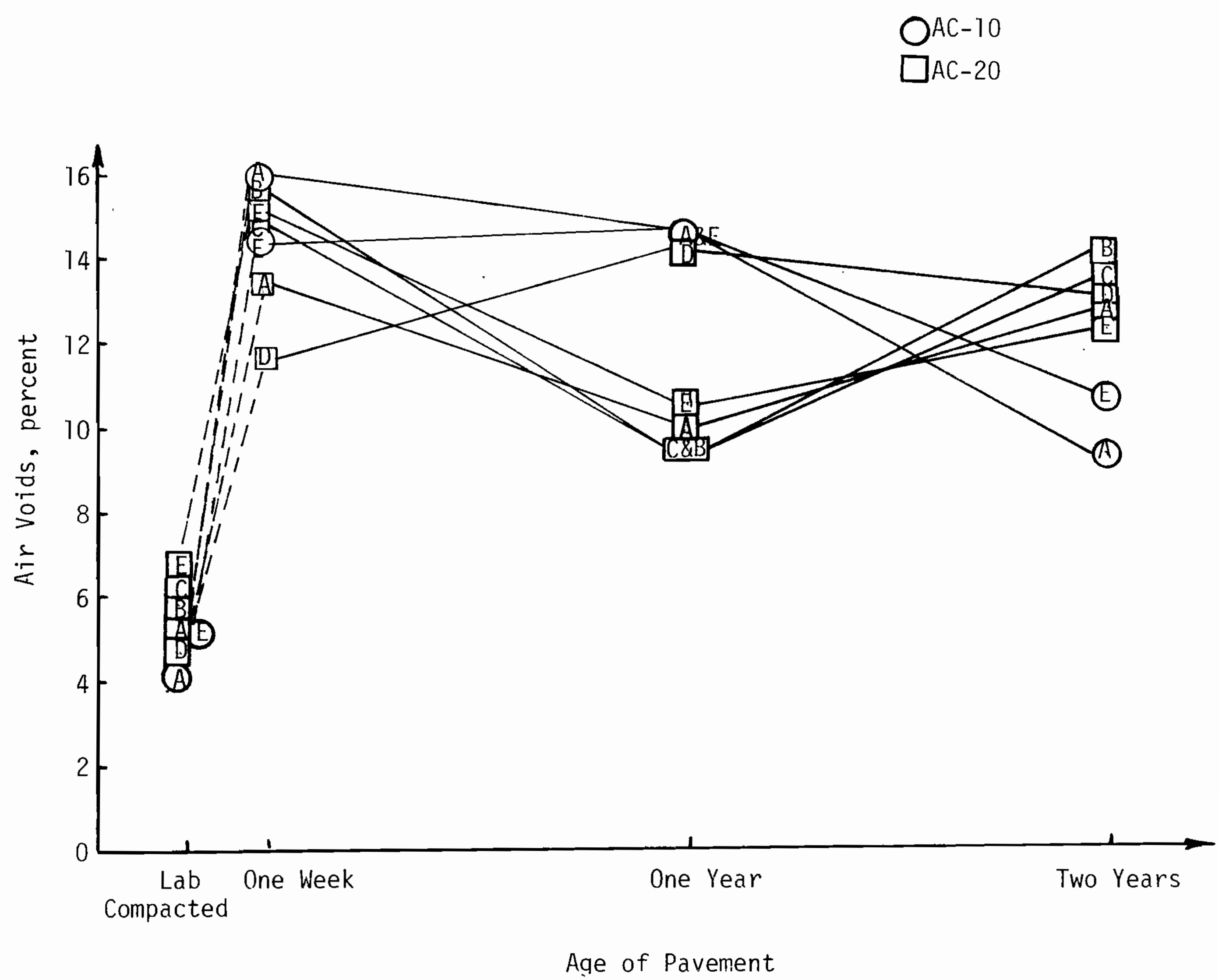

Figure 19. Percent Air Voids versus Pavement Age for Dickens Cores.

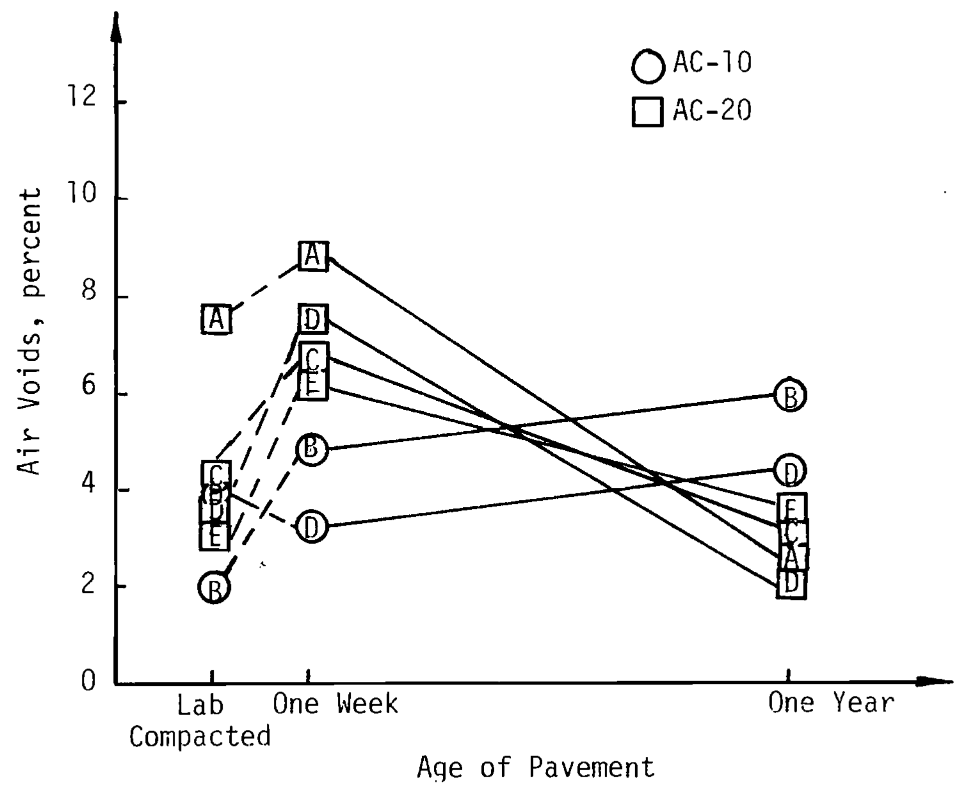

Figure 20. Percent Air Voids versus Pavement Age for Lufkin Cores.

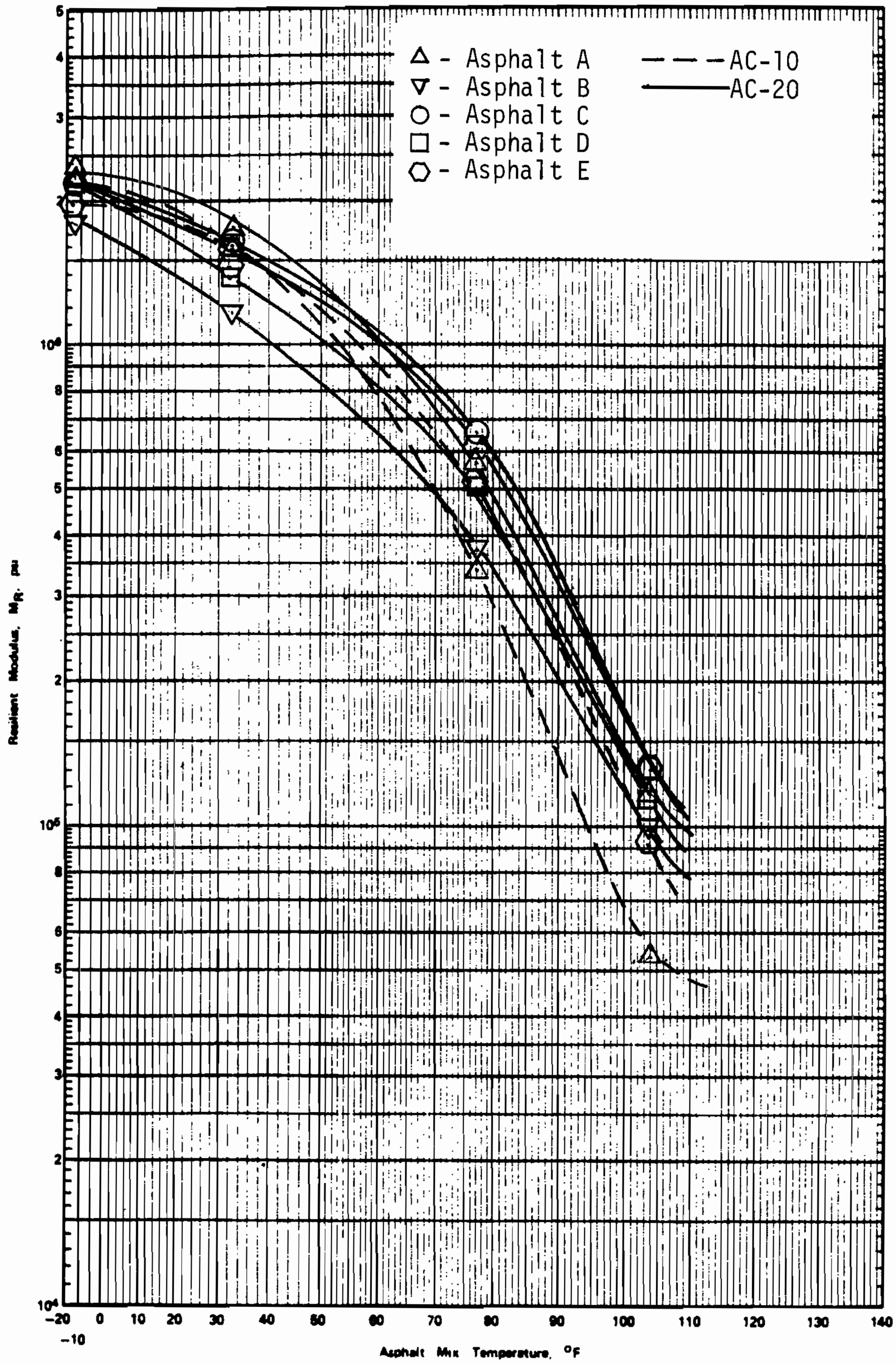

Figure 21. Resilient Modulus Versus Temperature for Dickens Laboratory Compacted Samples.

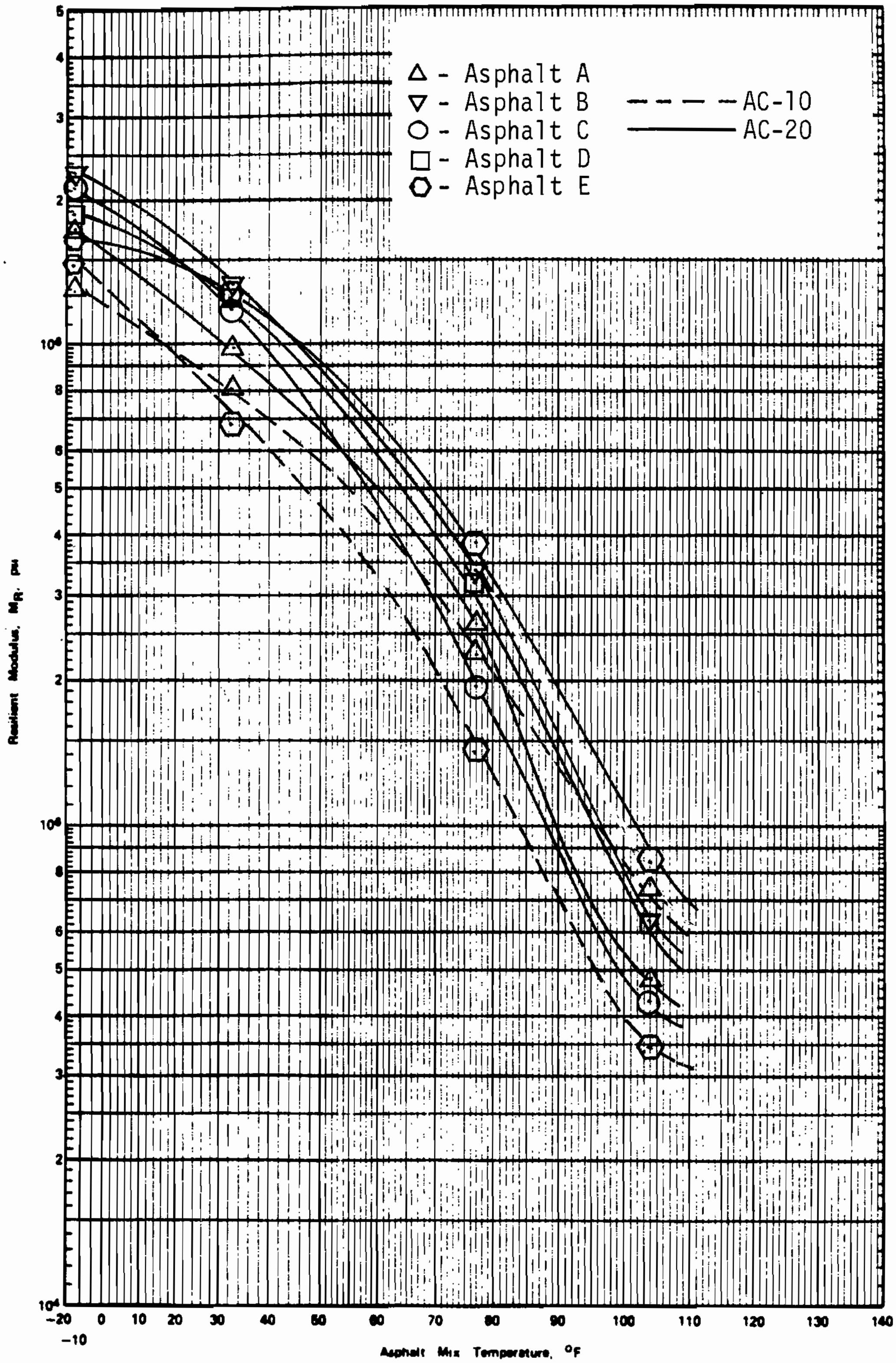

Figure 22. Resilient Modulus Versus Temperature for Dickens One Year Cores.

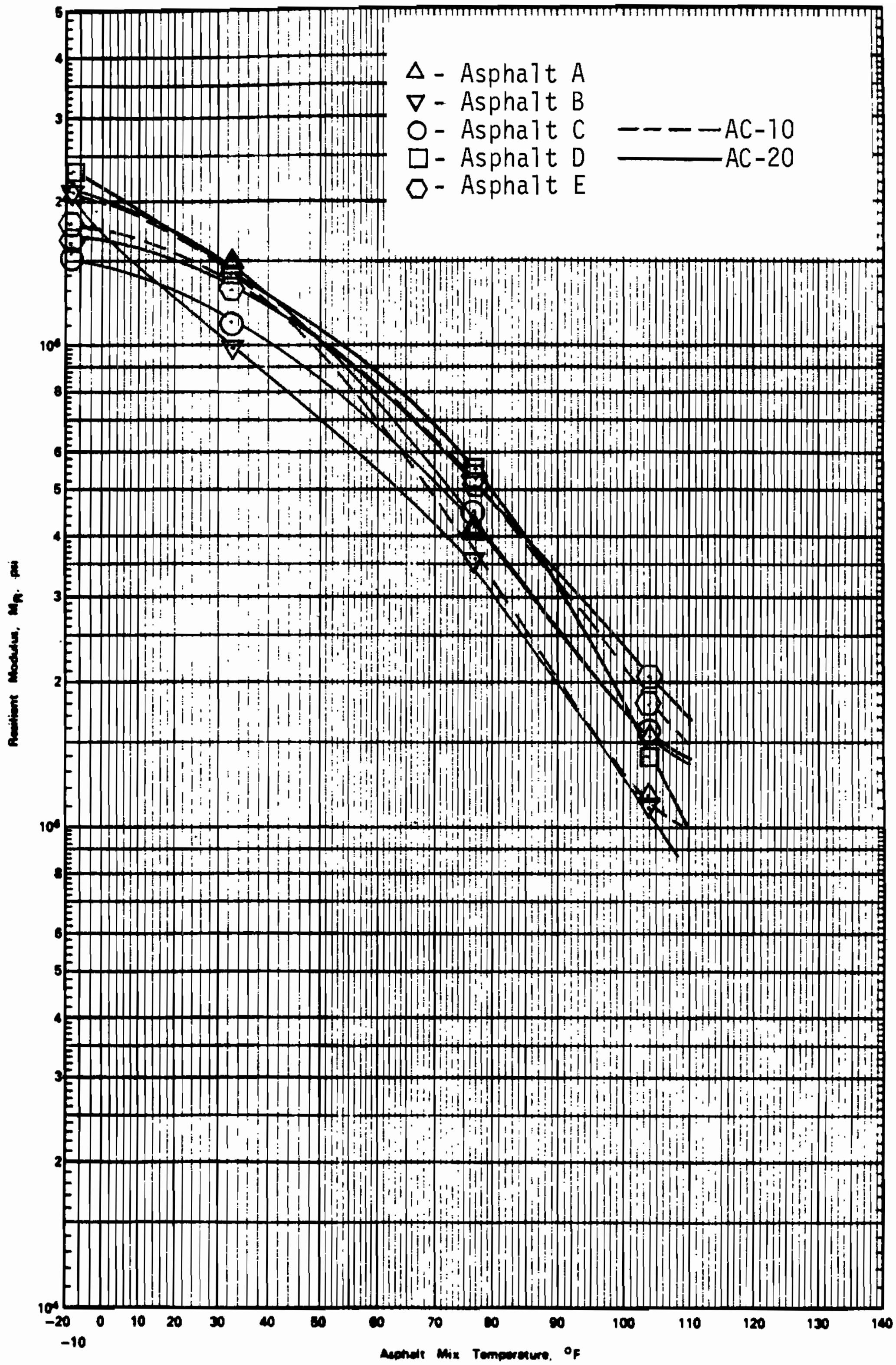

Figure 23. Resilient Modulus Versus Temperature for Dickens Two Year Cores.

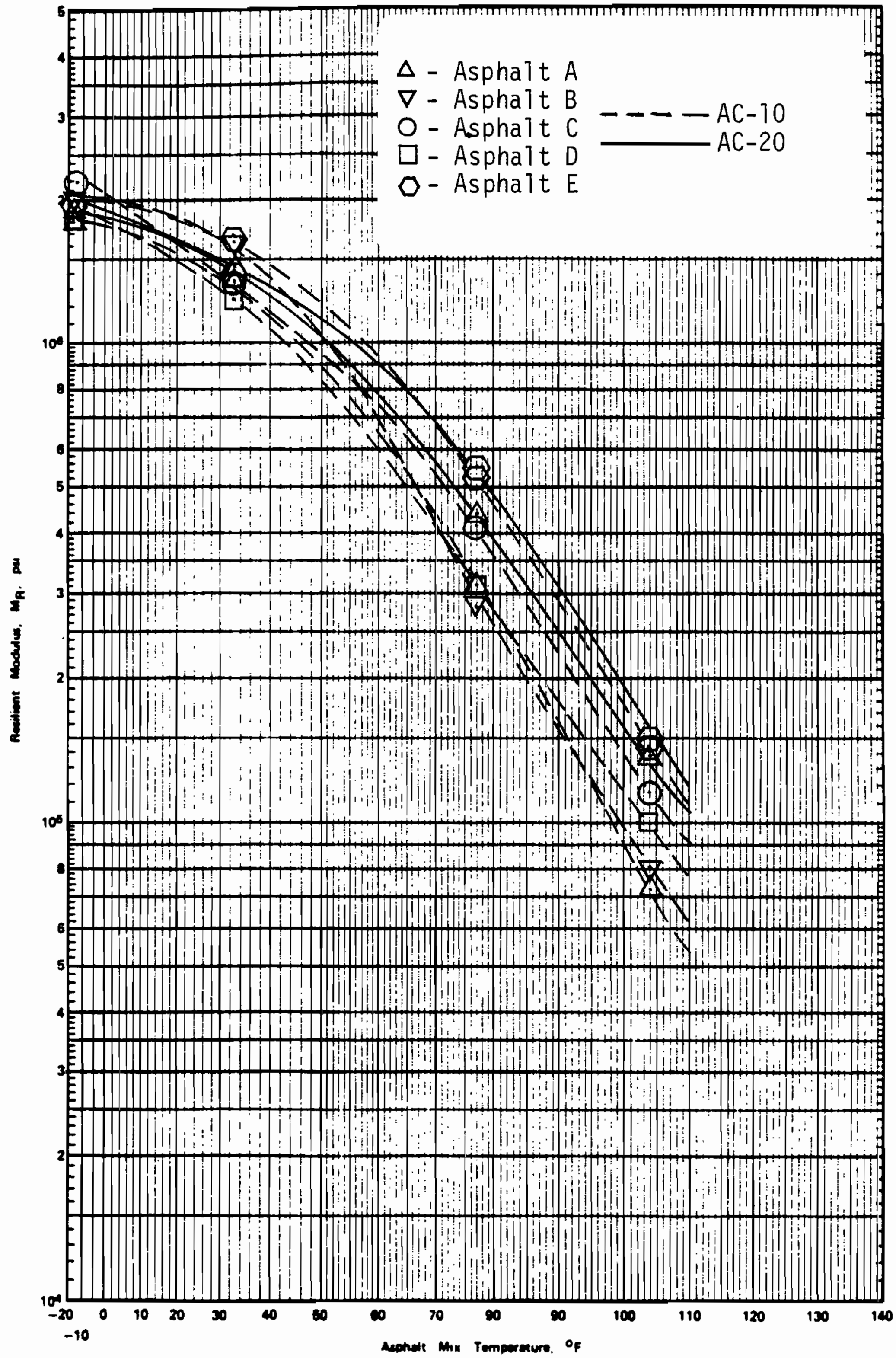

Figure 24. Resilient Modulus Versus Temperature for Dumas Laboratory Compacted Samples.

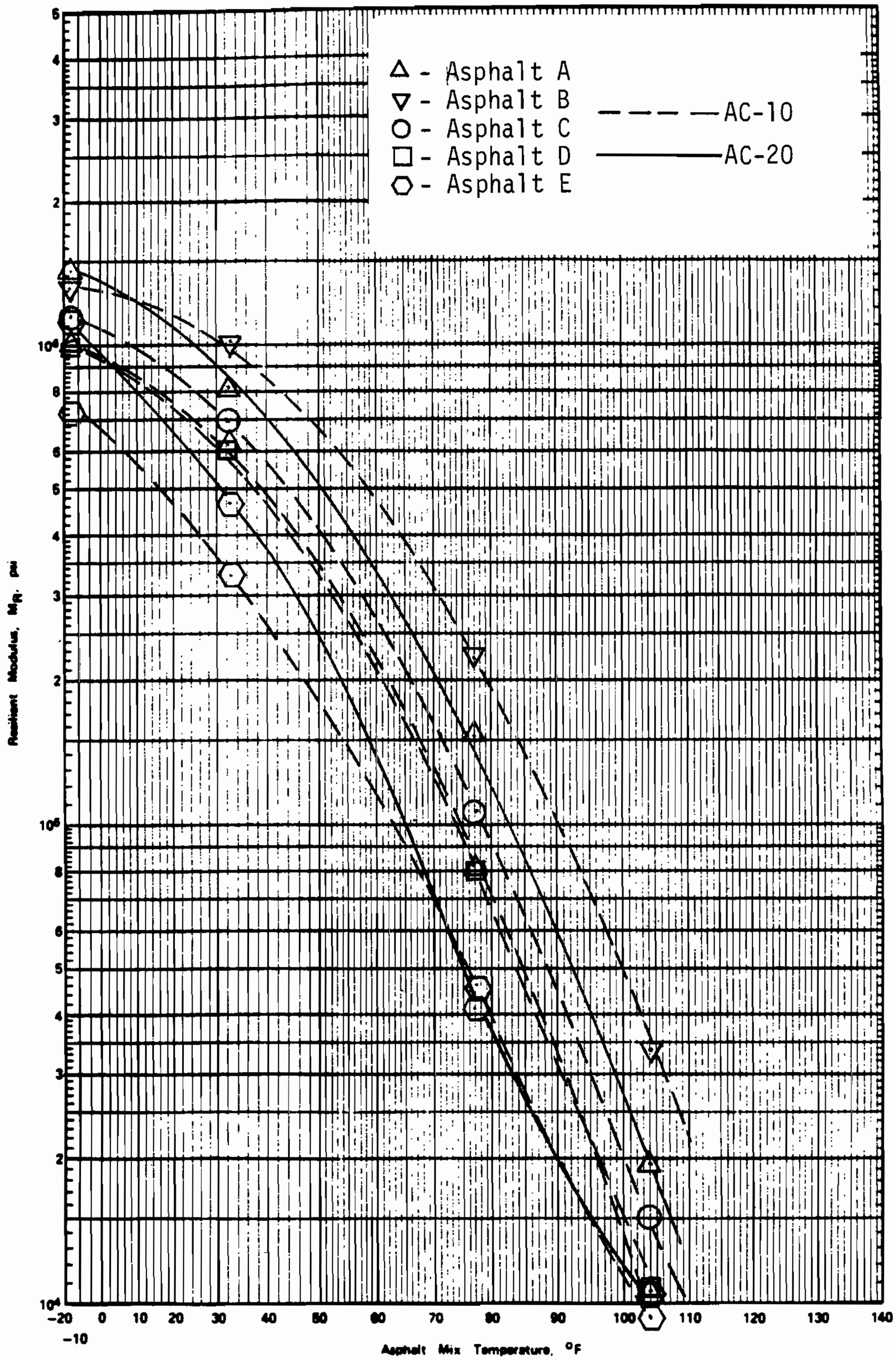

Figure 25. Resilient Modulus Versus Temperature for Dumas One Week Cores.

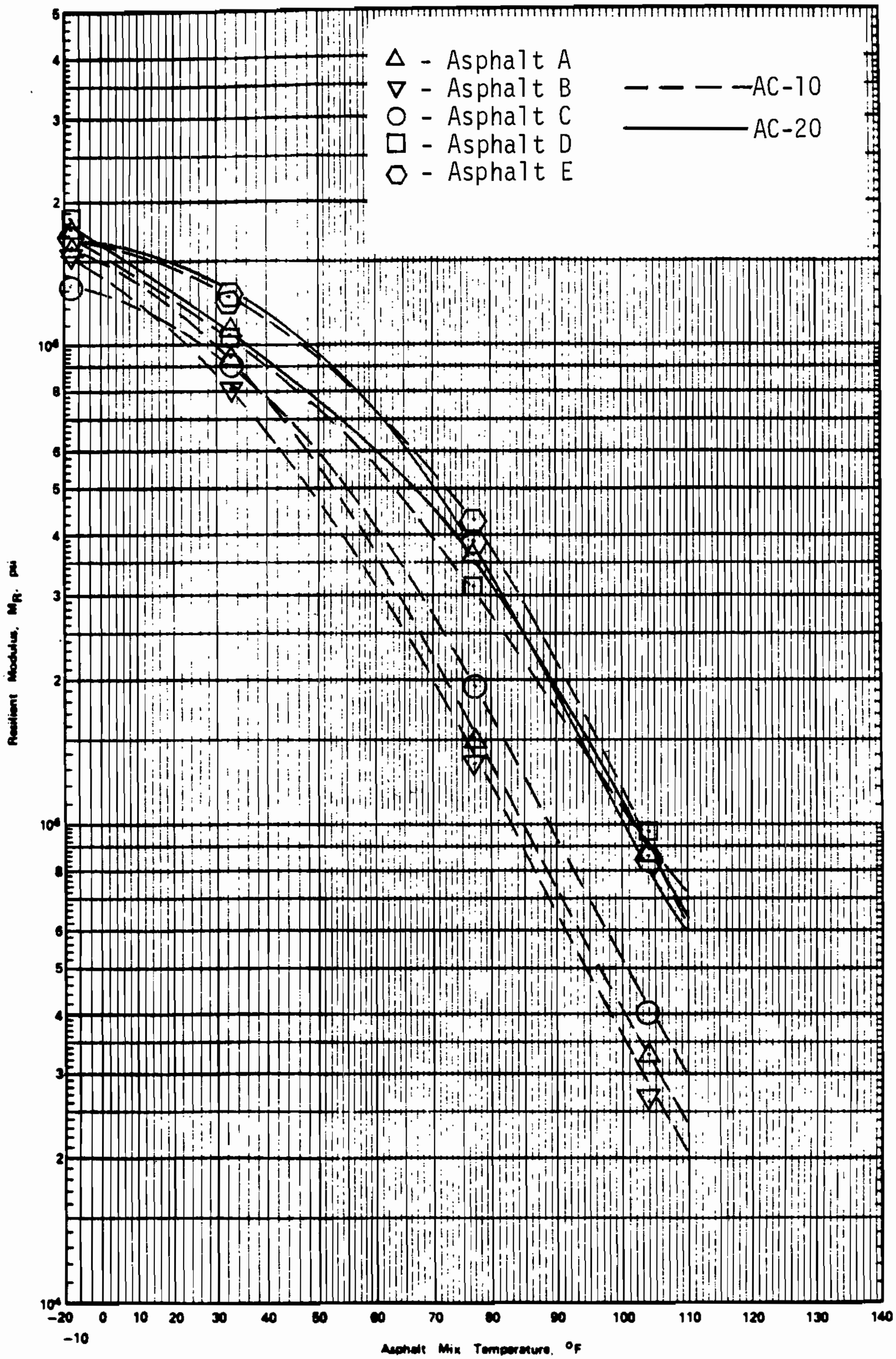

Figure 26. Resilient Modulus Versus Temperature for Dumas One Year Cores.

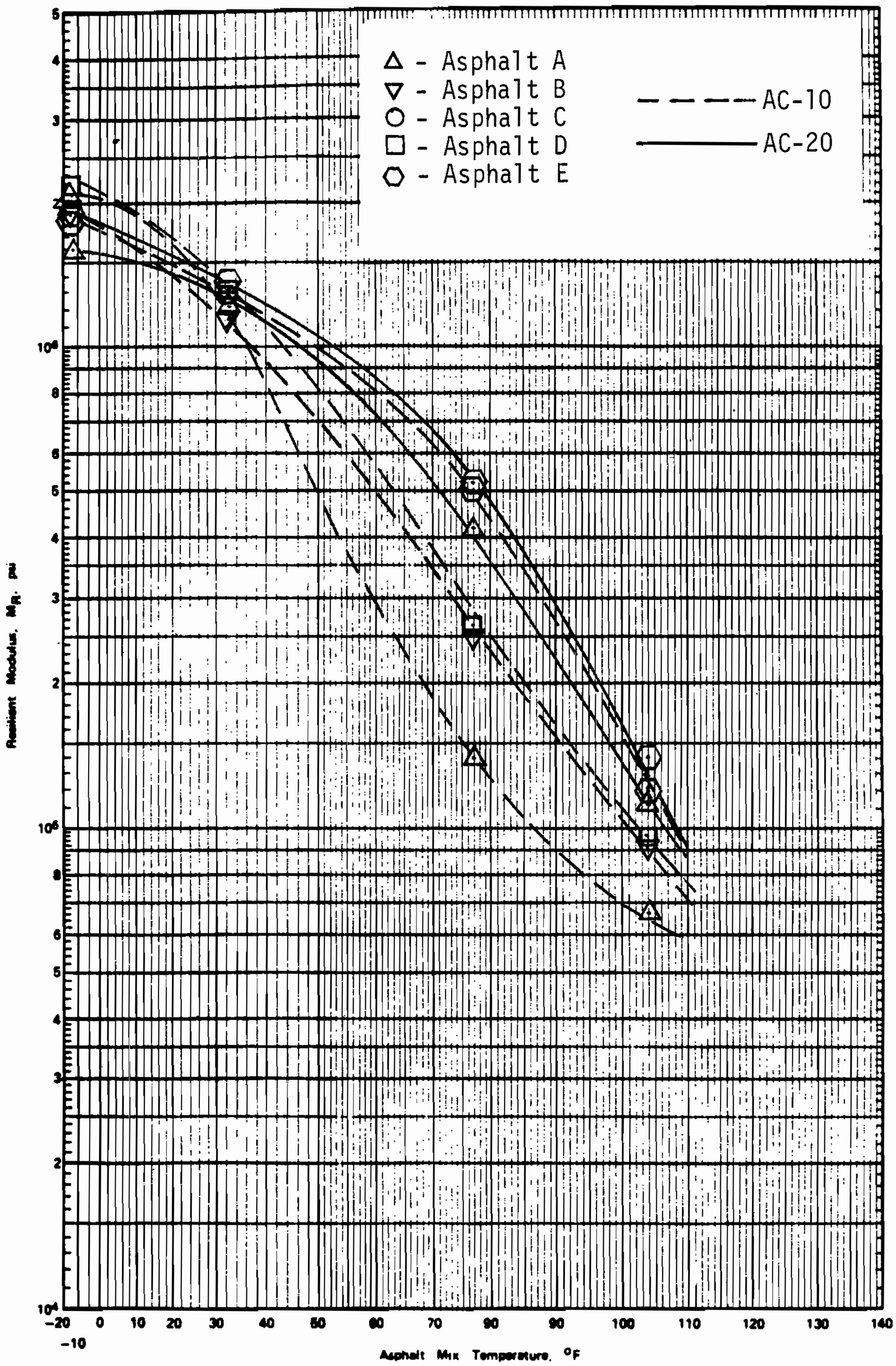

Figure 27. Resilient Modulus Versus Temperature for Dumas Two Year Cores.

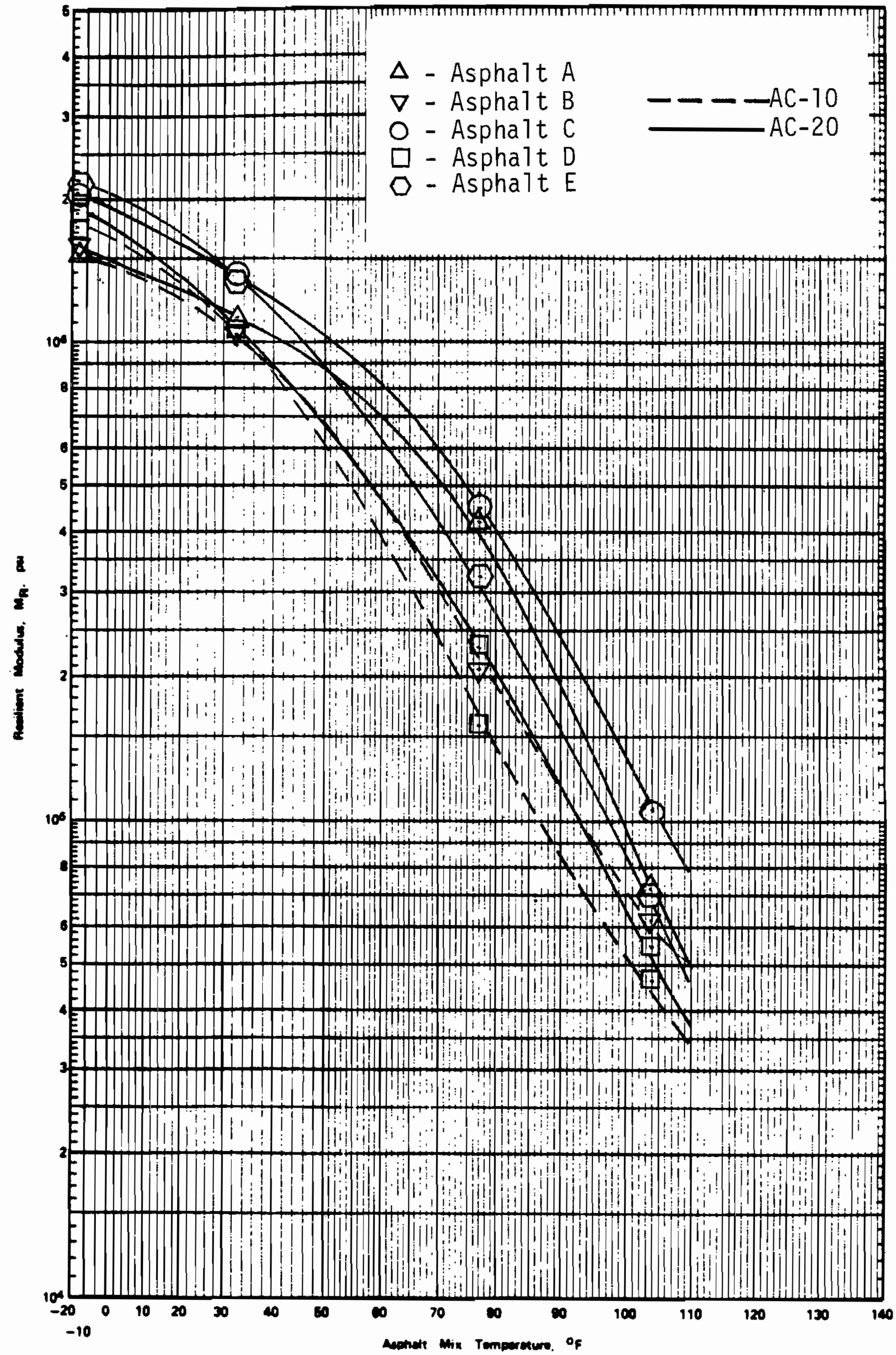

Figure 28. Resilient Modulus Versus Temperature for Lufkin Laboratory Compacted Samples.

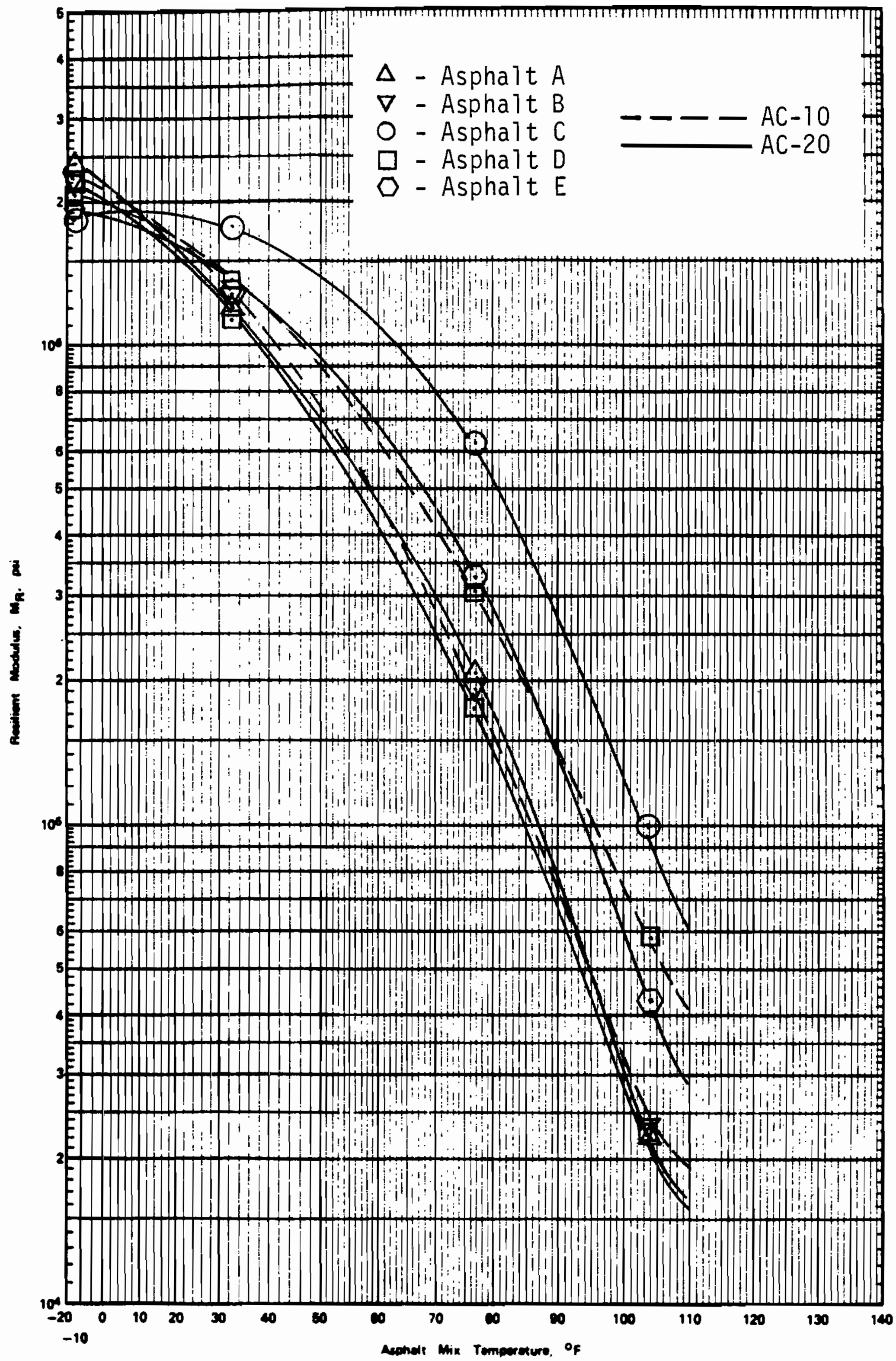

Figure 29. Resilient Modulus Versus Temperature for Lufkin One Week Cores.

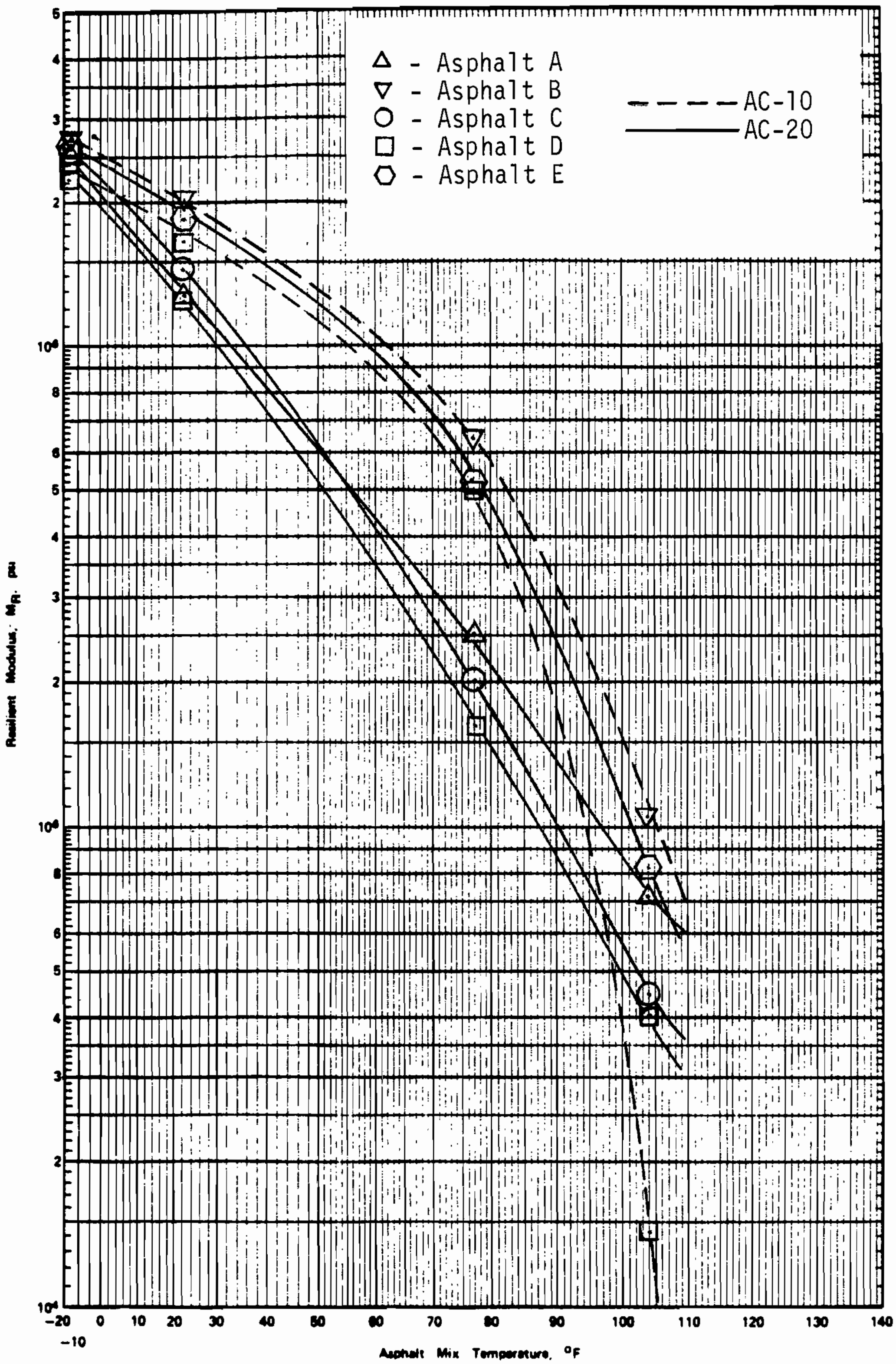

Figure 30. Resilient Modulus Versus Temperature for Lufkin One Year Cores.

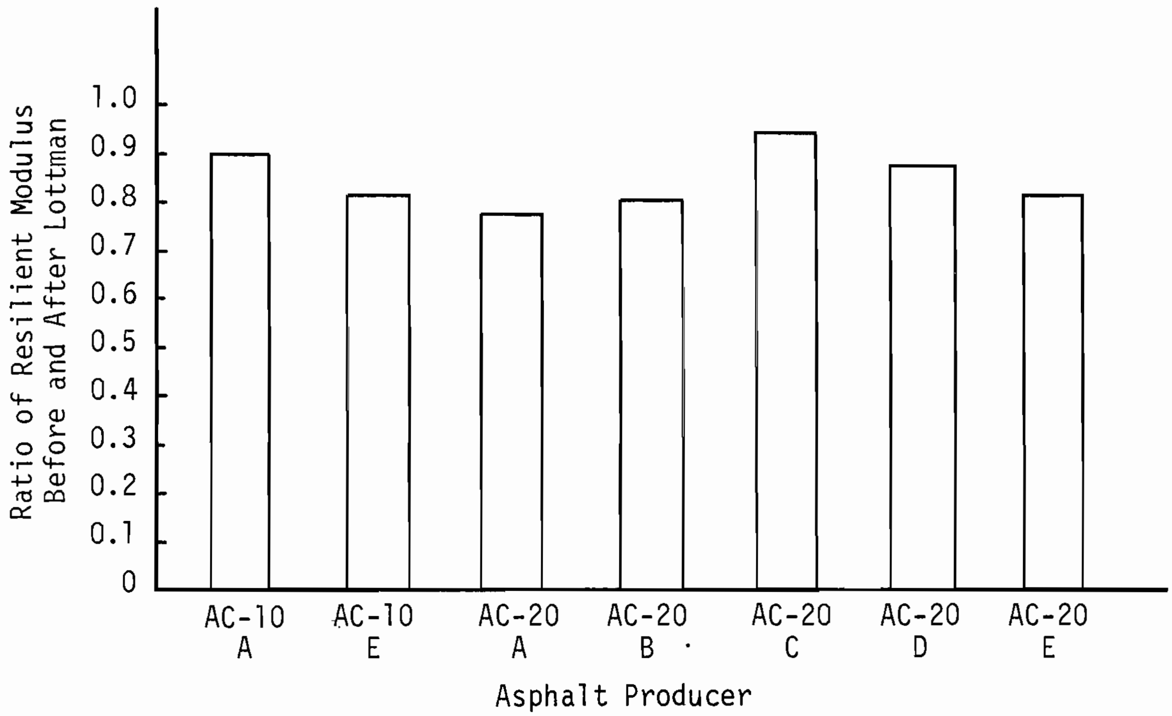

Figure 31. Ratio of Resilient Modulus Before and After Lottman (76) for Dickens Laboratory Compacted Samples.

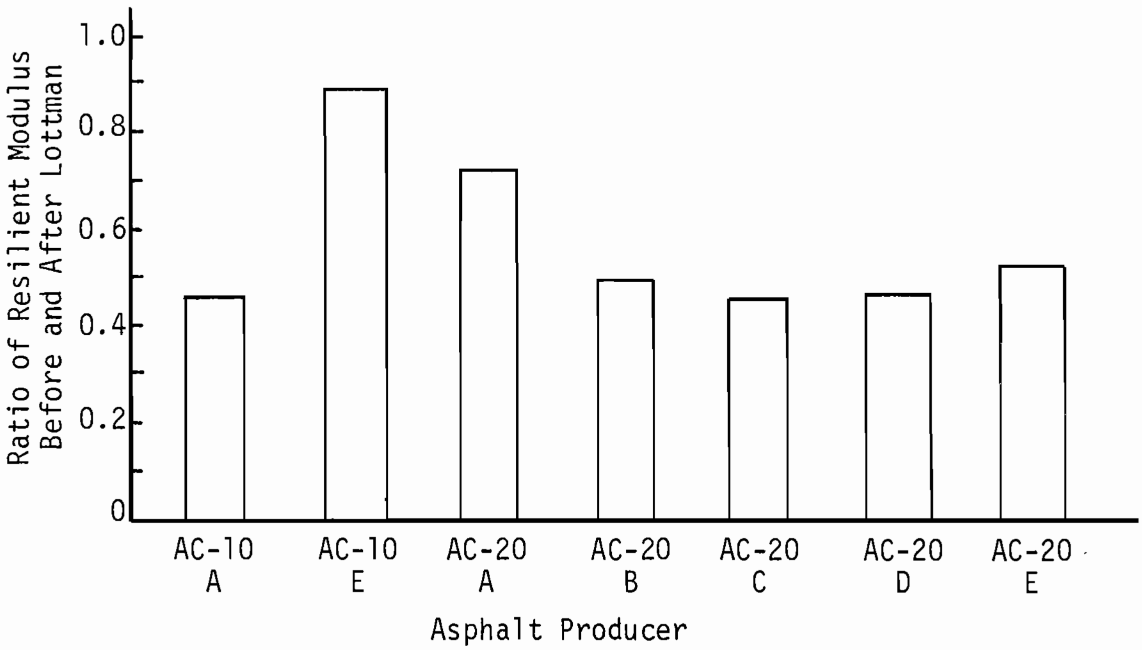

Figure 32a. Ratio of Resilient Modulus Before and After Lottman (76) for Dickens One Year Cores.

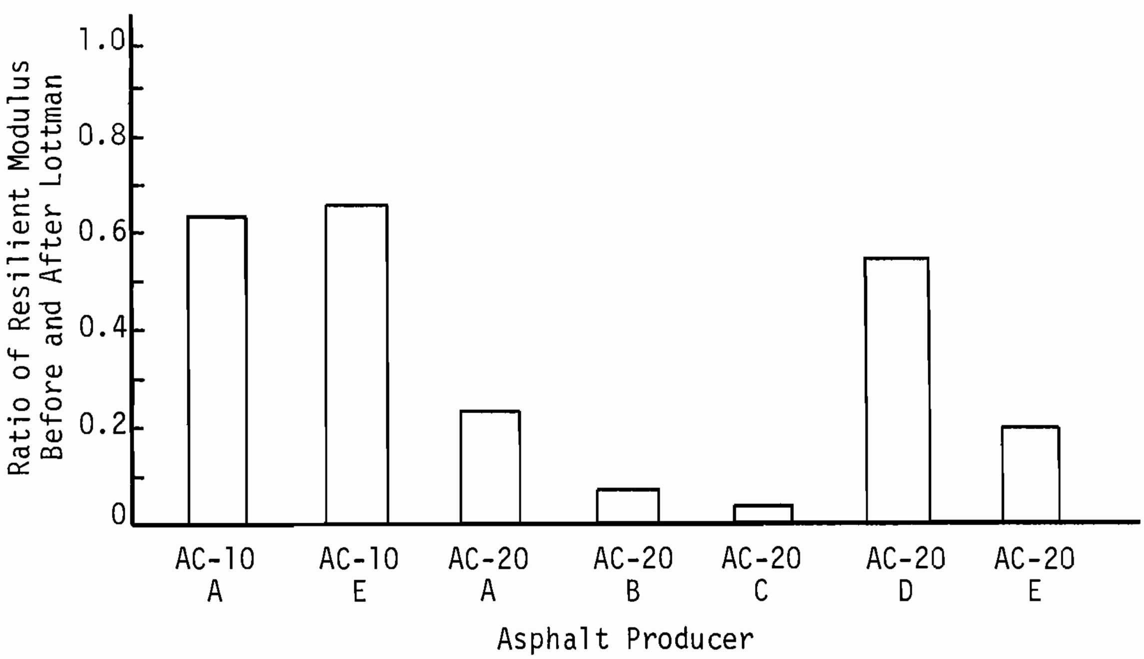

Figure 32b. Ratio of Resilient Modulus Before and After Lottman (76) for Dickens Two Year Cores.

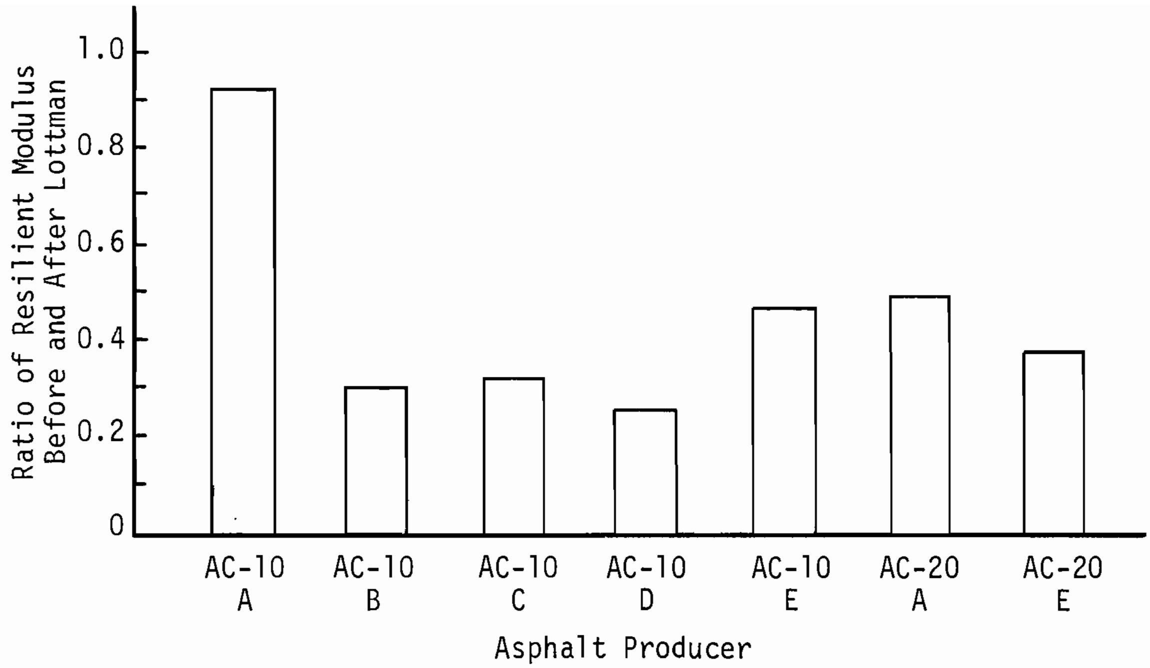

Figure 33a. Ratio of Resilient Modulus Before and After Lottman (76) for Dumas Laboratory Compacted Samples.

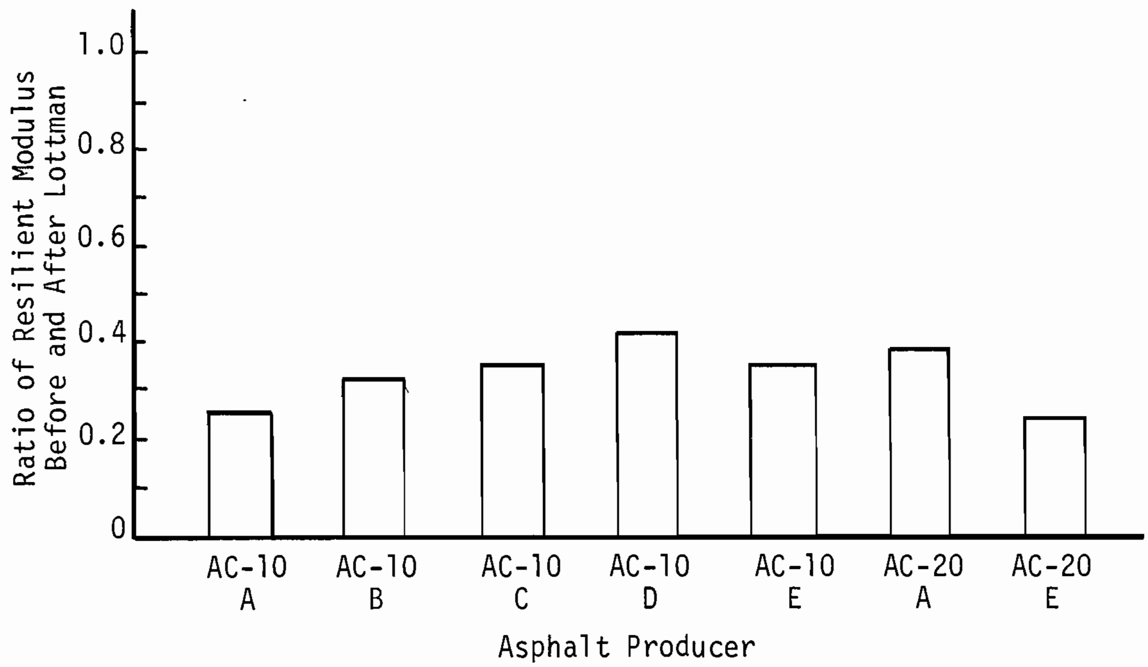

Figure 33b. Ratio of Resilient Modulus Before and After Lottman (76) for Dumas One Week Cores.

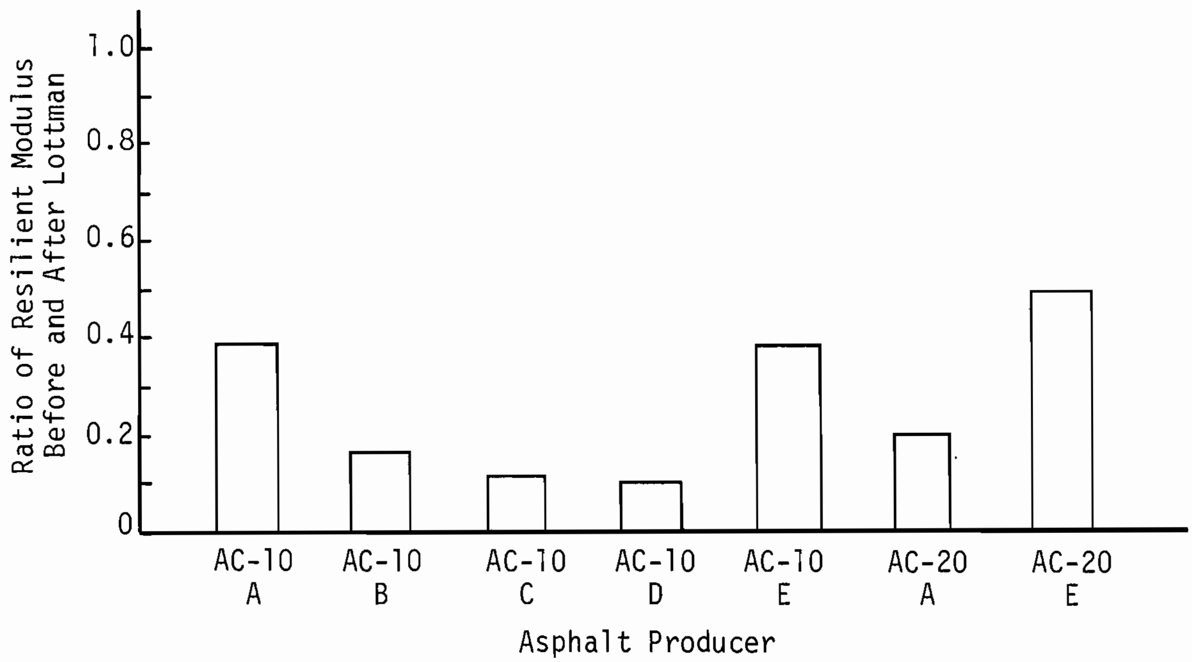

Figure 34a. Ratio of Resilient Modulus Before and After Lottman (76) for Dumas One Year Cores.

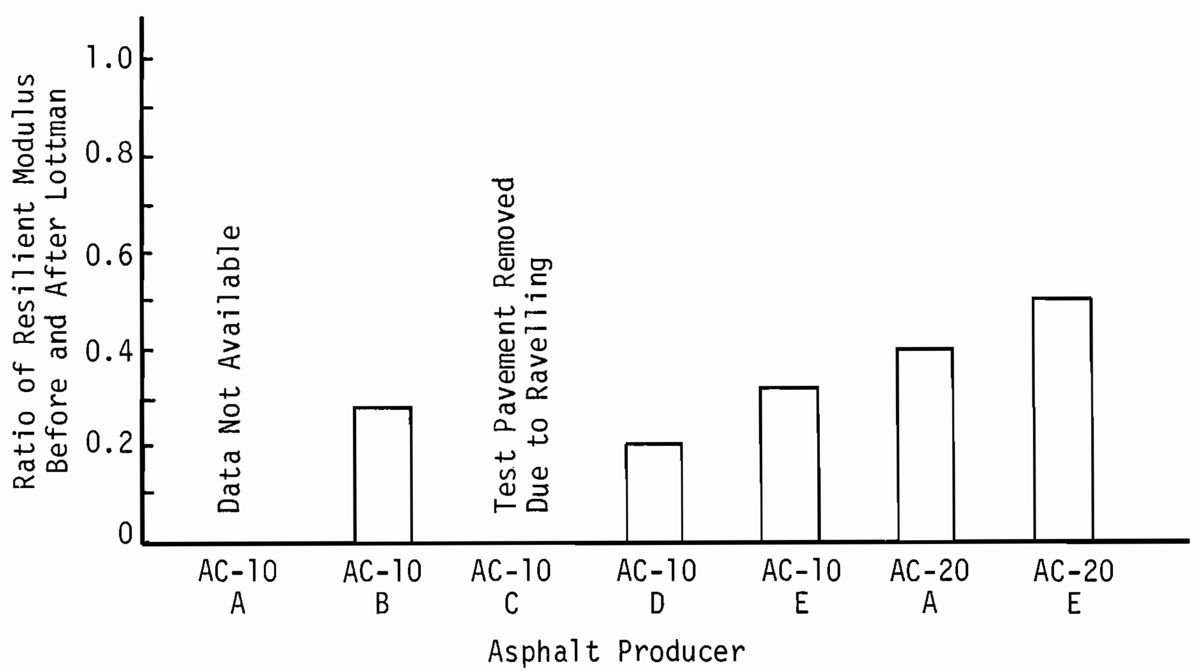

Figure 34b. Ratio of Resilient Modulus Before and After Lottman (76) for Dumas Two Year Cores.

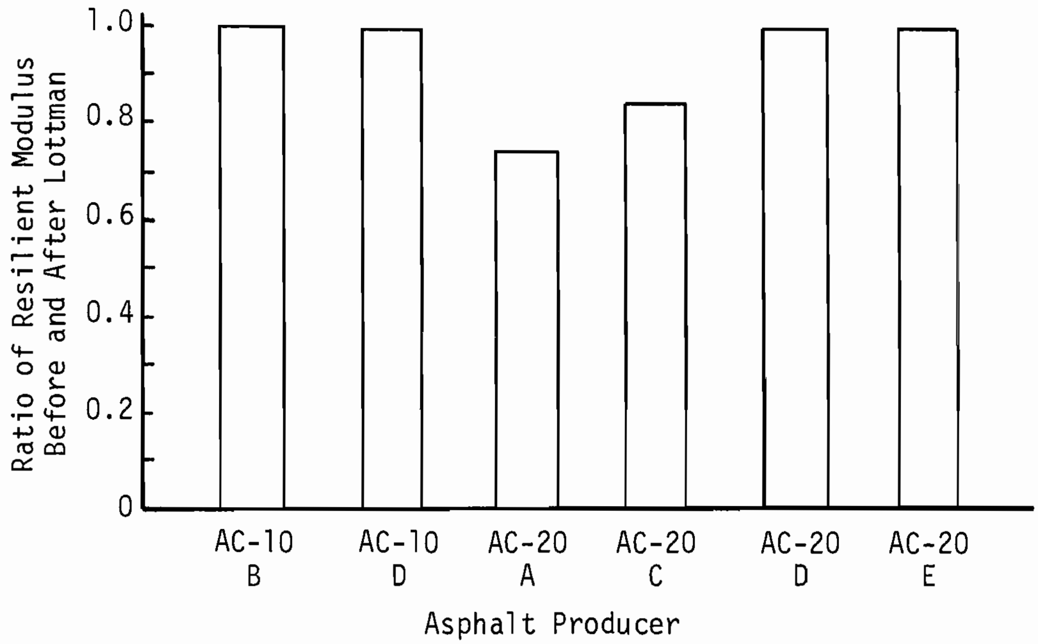

Figure 35. Ratio of Resilient Modulus Before and After Lottman (76) for Lufkin Laboratory Compacted Samples.

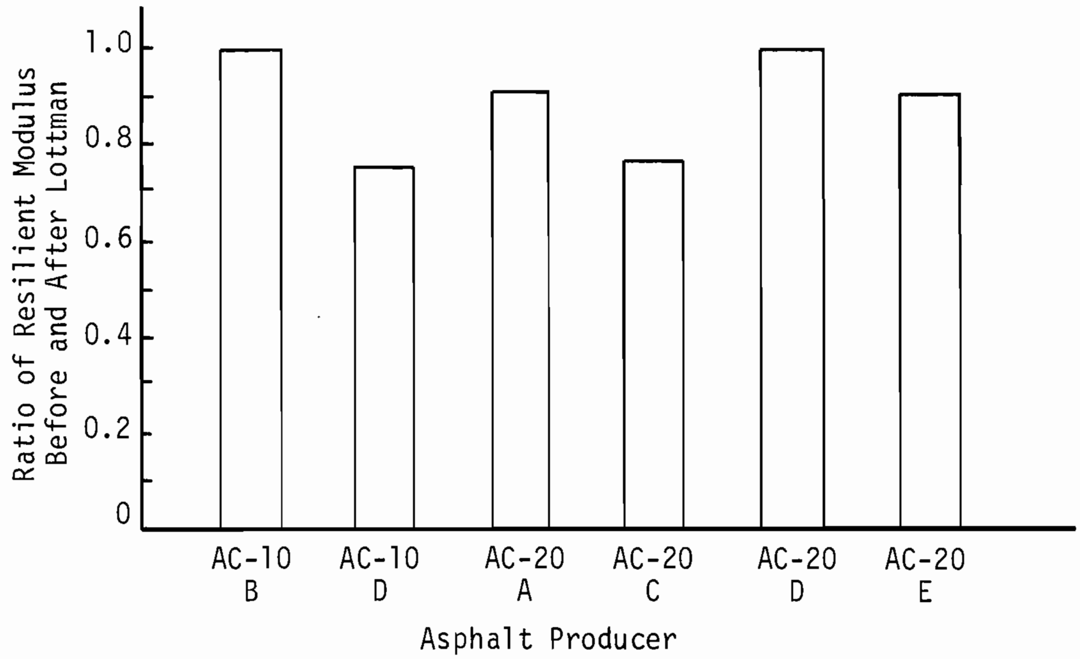

Figure 36a. Ratio of Resilient Modulus Before and After Lottman (76) for Lufkin One Week Cores.

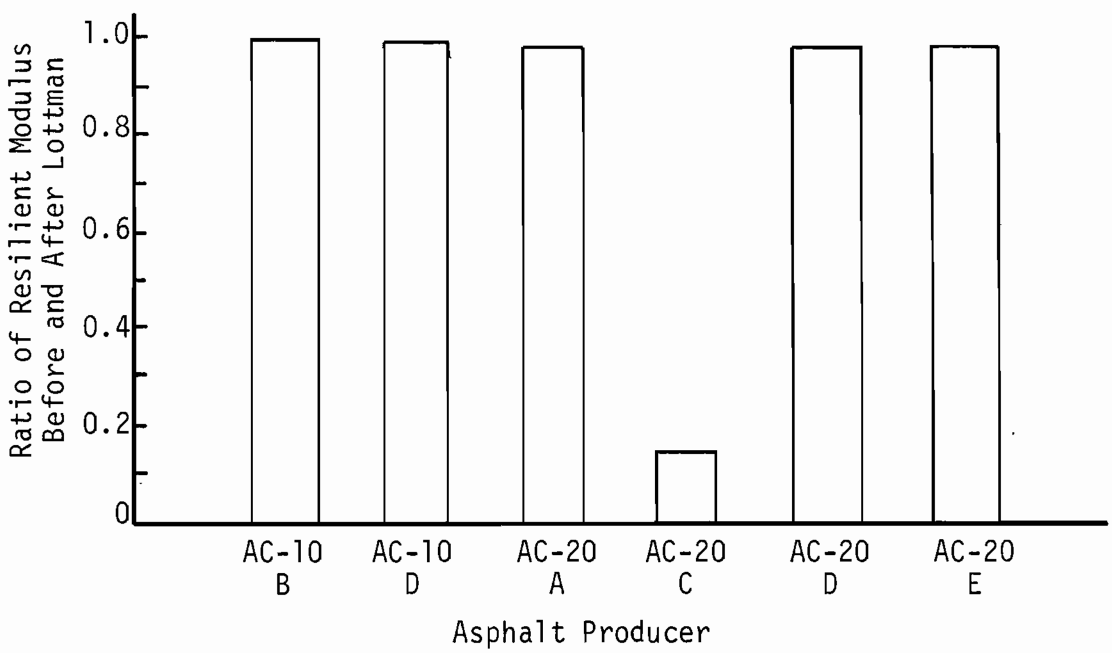

Figure 36b. Ratio of Resilient Modulus Before and After Lottman (76) for Lufkin One Year Cores.

Indirect Tension Test. Like the resilient modulus test, the indirect tension test is also binder sensitive. Tensile strength is plotted for the laboratory molded samples and field cores in Figures 37 through 39. When comparing strength of the asphalts, no correlation was evident. Figures 40 through 42 show the ratios of tensile strength before and after Lottman procedures. Again, the Lufkin cores retained most of their original strength.

Hveem Stability. Hveem stability values are plotted before and after Lottman procedures in Figure 43 through 47. There does not appear to be any consistent difference between asphalt producers. This is anticipated since Hveem stability is much more dependent on aggregate properties than asphalt properties.

Typical field compacted mixtures (pavement cores) contain variables which hinder data analysis. The excessive air void contents in Dumas and Dickens caused the mixtures to exhibit very low values of stability, strength and stiffness. Asphalt content also varied enough to significantly affect mixture properties. Tables in Appendix C illustrate the extremely low values of stability, strength and stiffness that can be obtained from "acceptable" pavements made from mixtures and using procedures which supposedly meet specifications. The point of this discussion is that compaction cannot be over emphasized.

The limited data in Figures 48 and 49 indicate that temperature susceptibility of the asphalt can adversely affect compaction. The lab compacted samples also show a slight trend toward greater voids (Figure 50) in the mixtures containing the more temperature susceptible asphalts; and they were compacted under controlled conditions at a temperature near 250^{o}F. At conventional compaction temperatures the more temperature susceptible asphalts should have the lower viscosities. It would follow then that lower asphalt viscosity adversely affects compaction. However, Figure 51 shows that air void content of pavement cores is independent of asphalt viscosity at 140^{o}F after the RTFOT. Therefore, if in fact the relationship between asphalt temperature susceptibility and air void

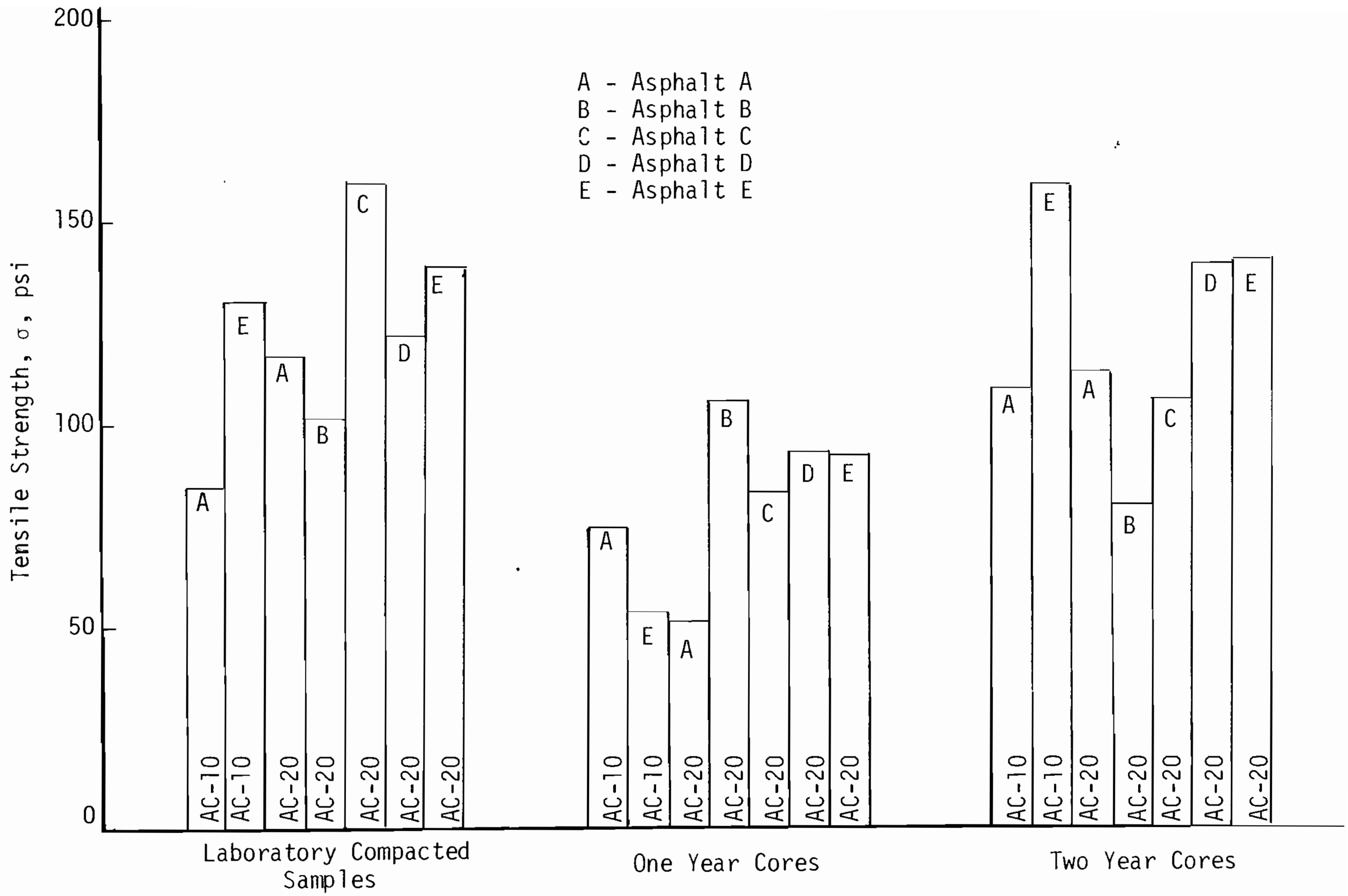

Figure 37. Tensile Strength of Dickens Samples.

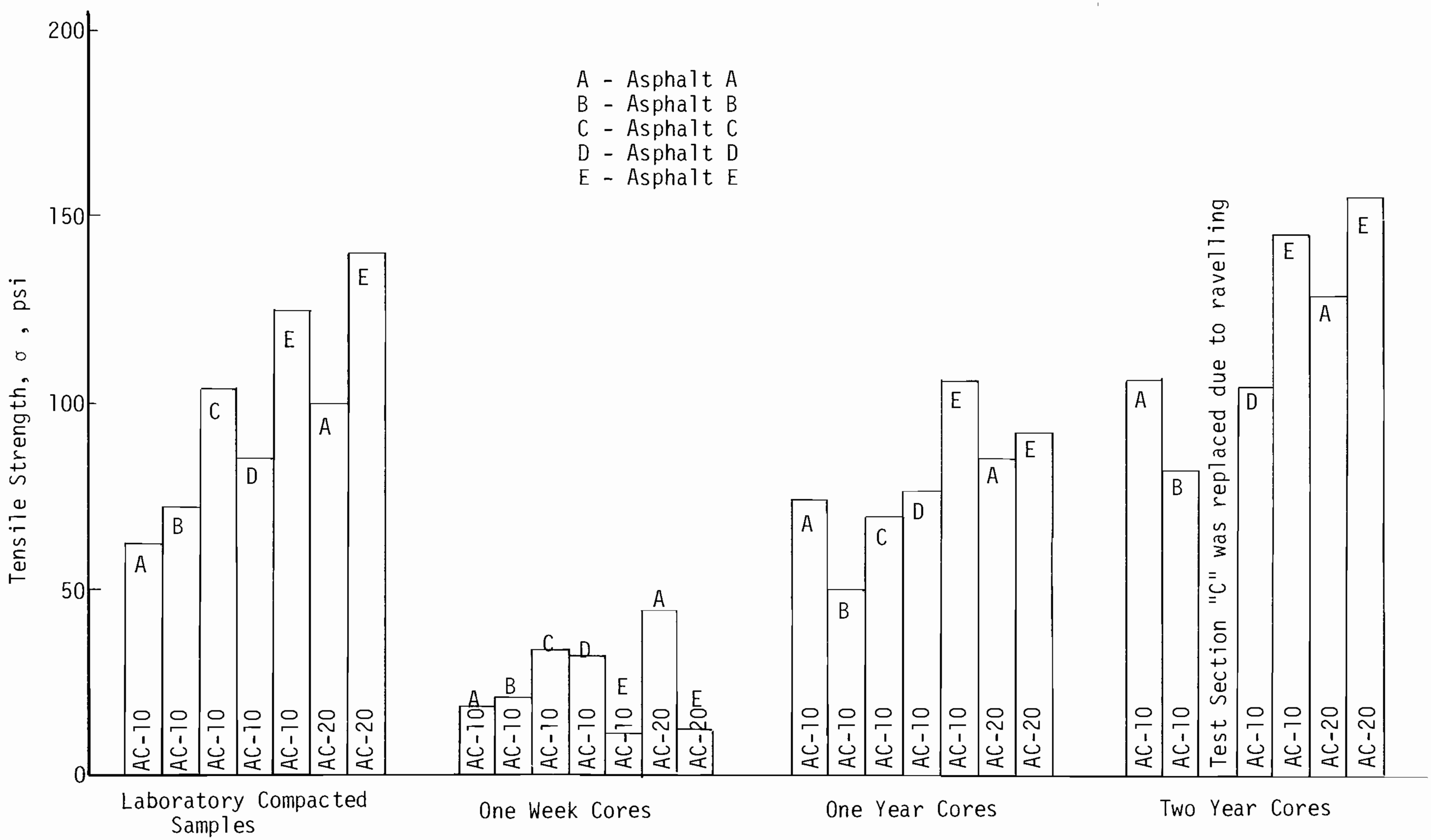

Figure 38. Tensile Strength of Dumas Samples.

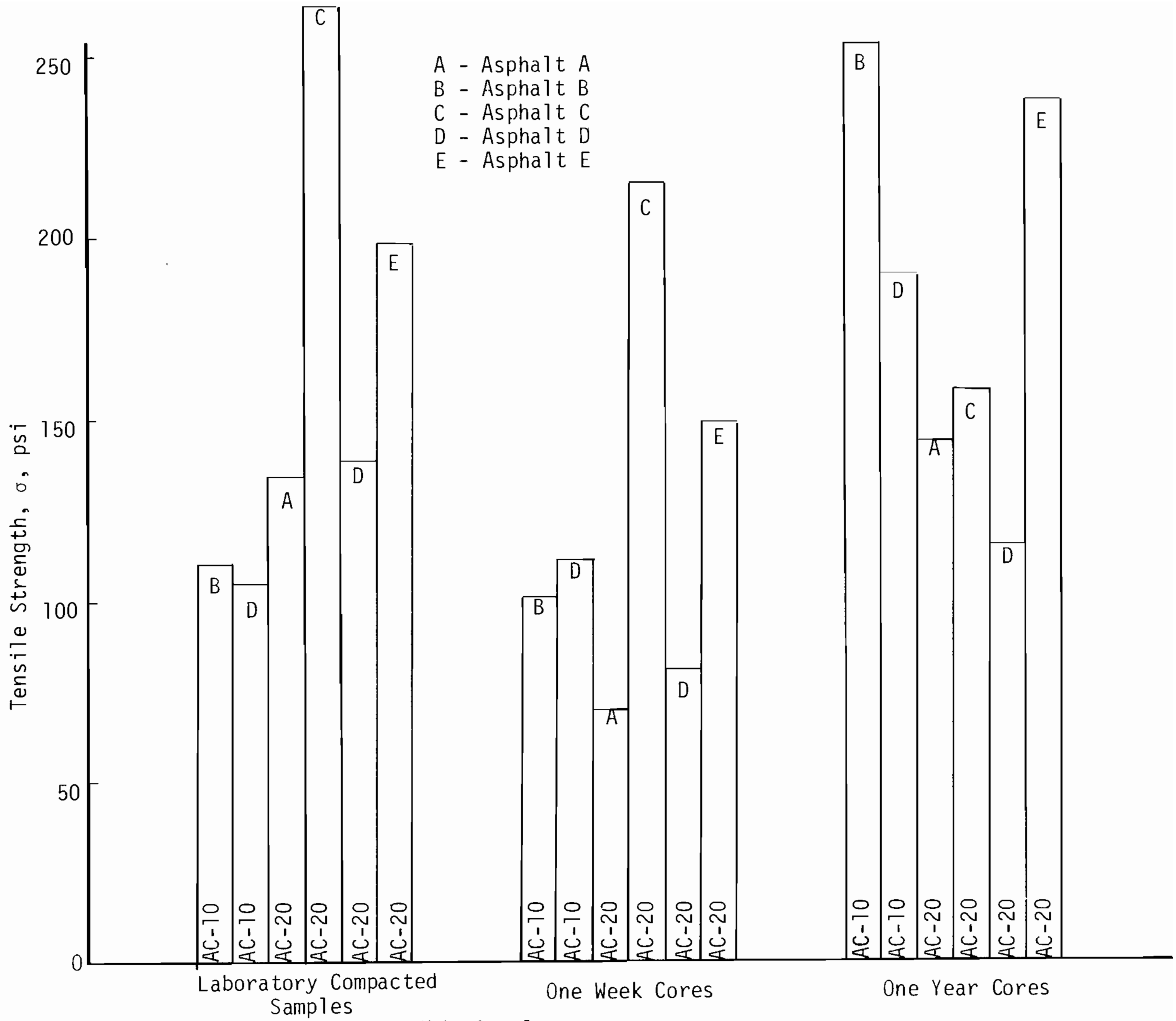

Figure 39. Tensile Strength of Lufkin Samples.

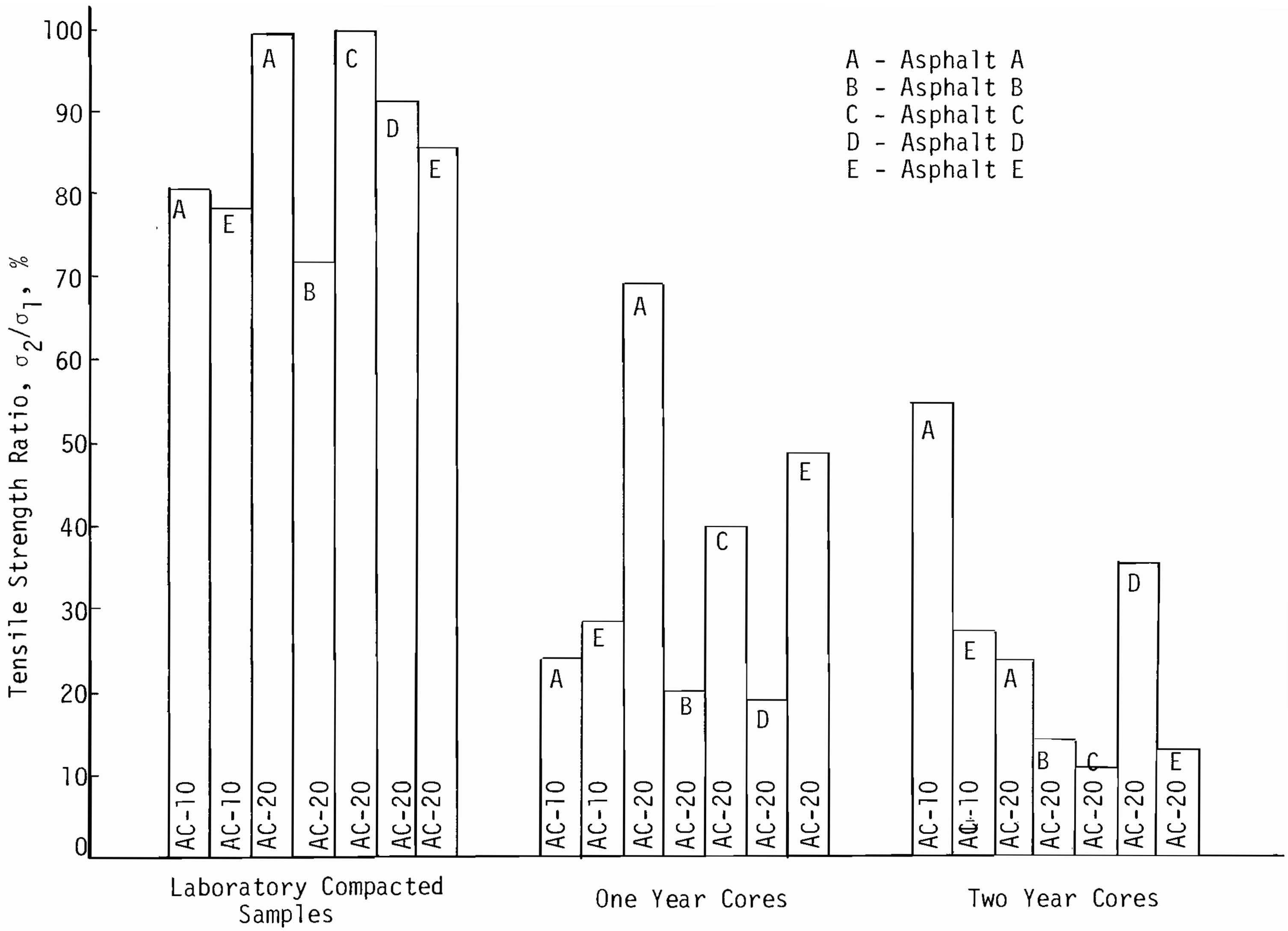

Figure 40. Ratio of Tensile Strengths, Before and After Lottman for Dickens Samples.

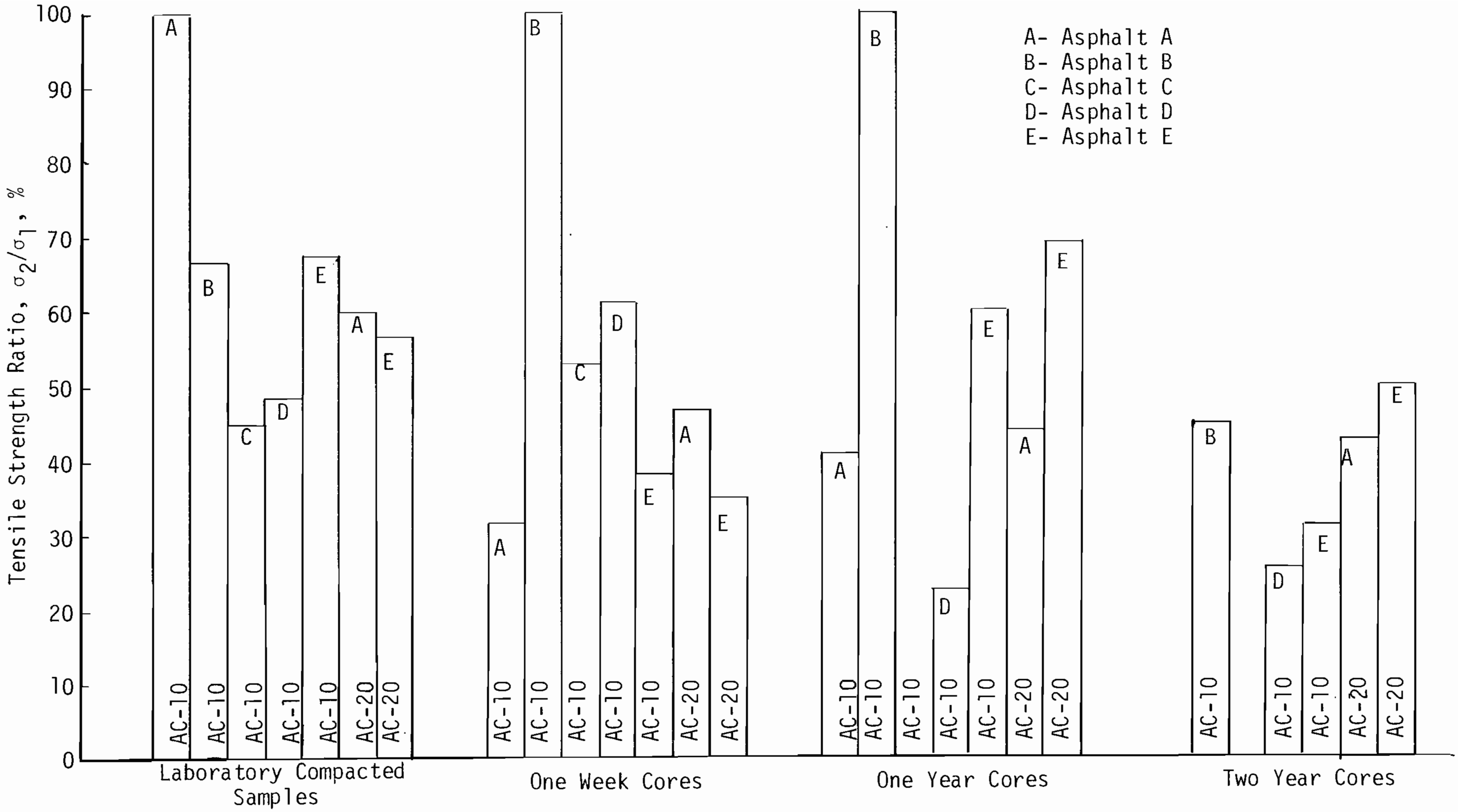

Figure 41. Ratio of Tensile Strengths, Before and After Lottman for Dumas Samples.

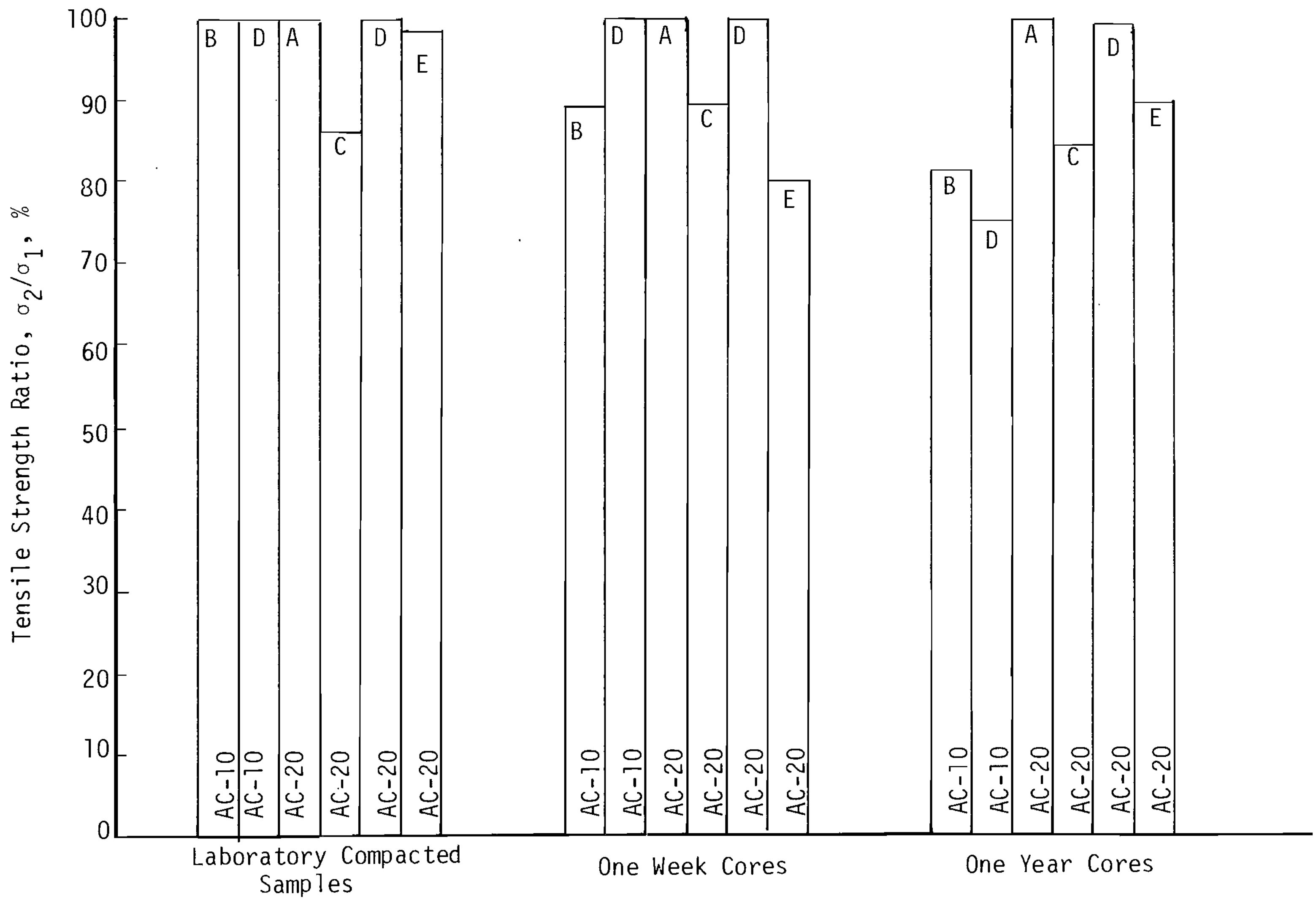

Figure 42. Ratio of Tensile Strengths, Before and After Lottman for Lufkin Samples.

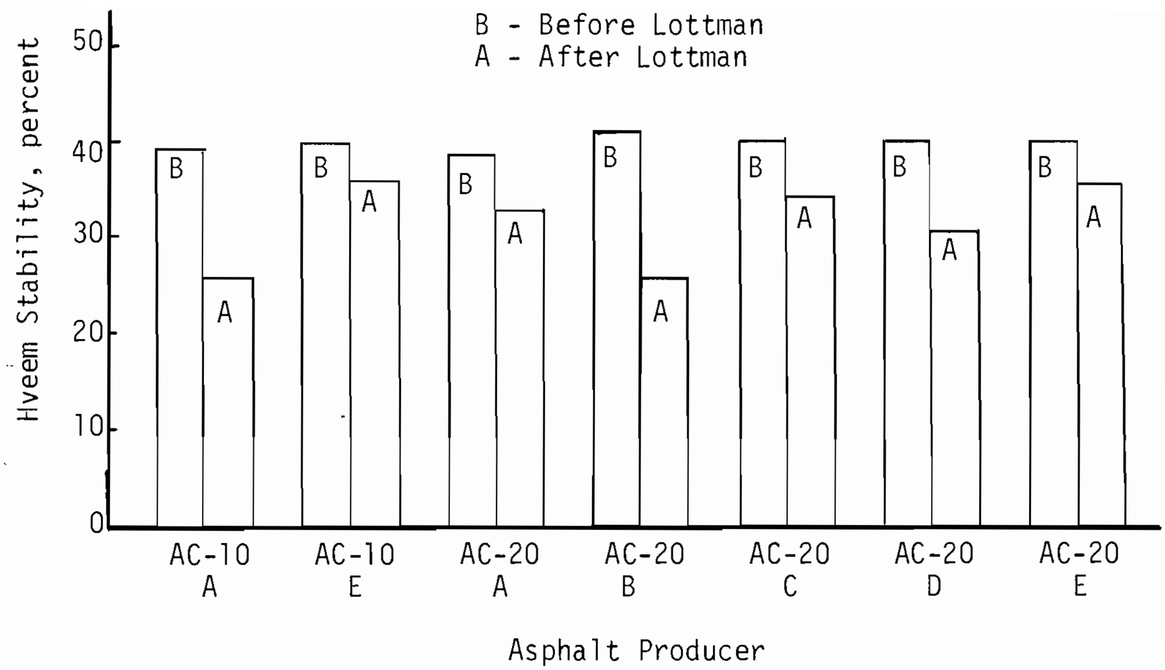

Figure 43. Hveem Stability Before and After Lottman for Dickens Laboratory Compacted Samples.

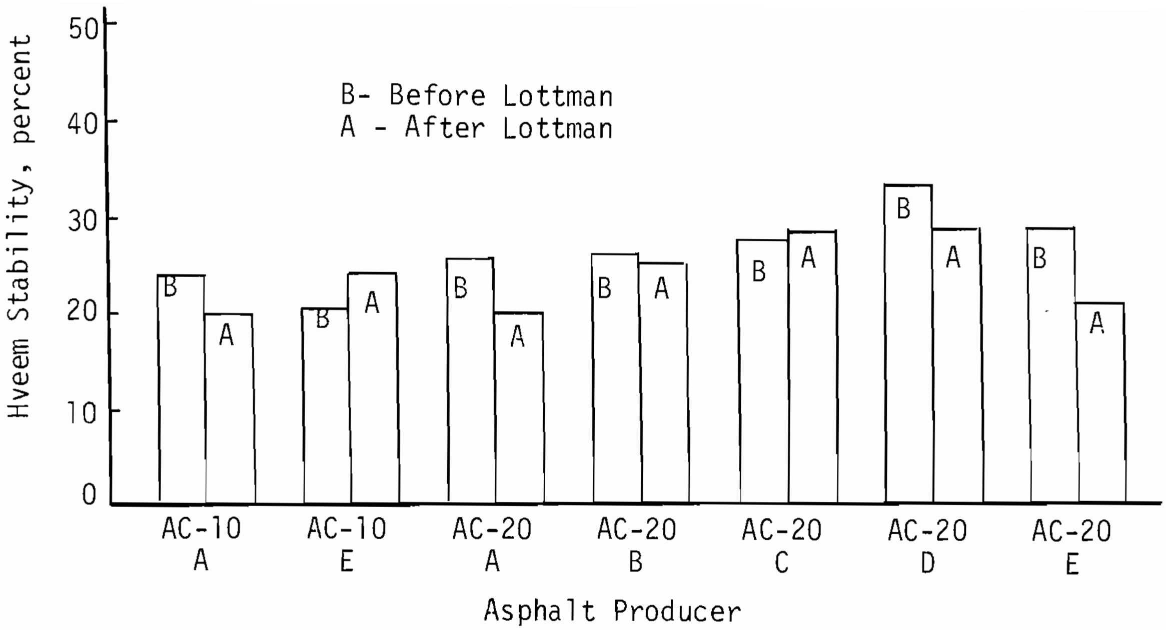

Figure 44a. Hveem Stability Before and After Lottman for Dickens One Year Cores.

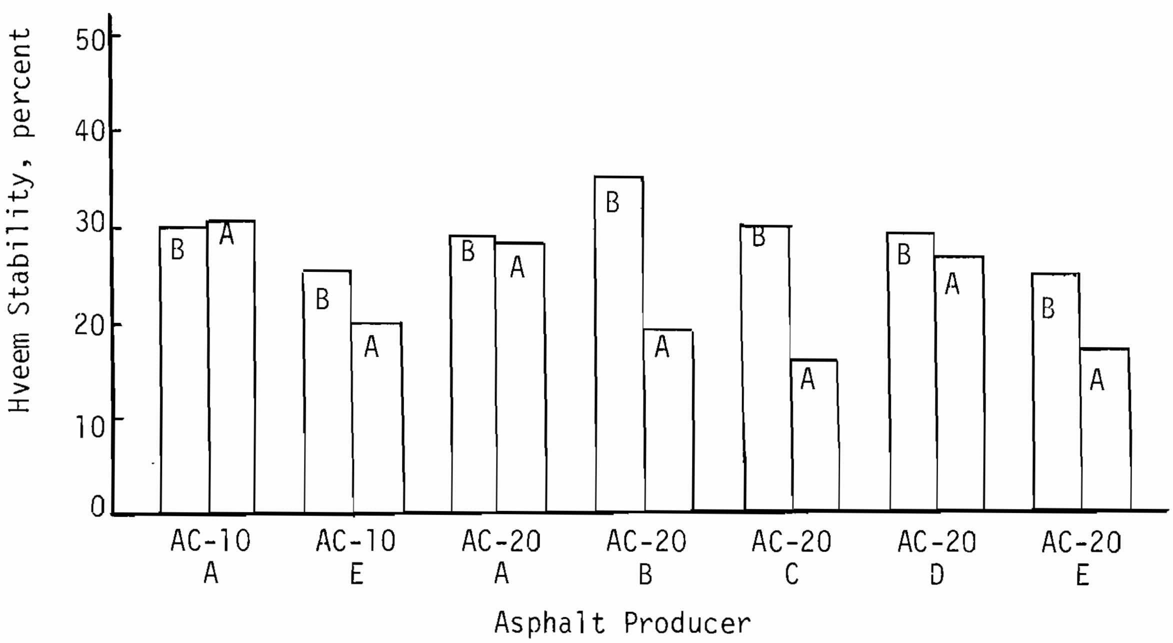

Figure 44b. Hveem Stability Before and After Lottman for Dickens One Year Cores.

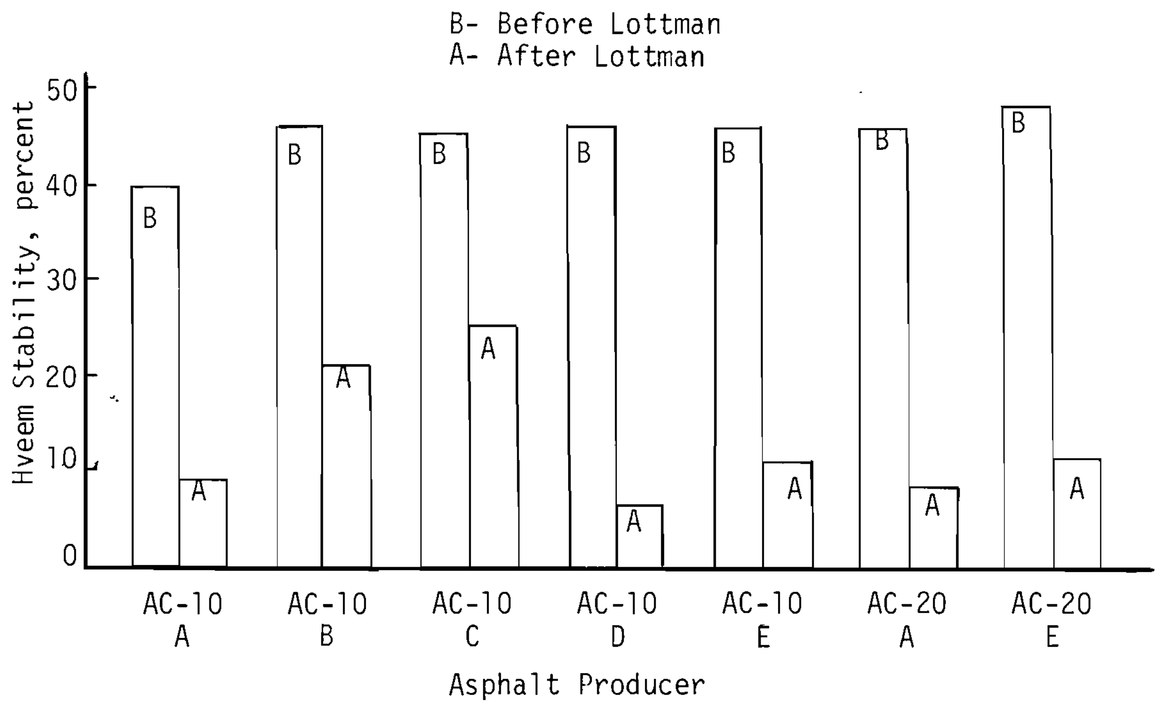

Figure 45a. Hveem Stability Before and After Lottman for Dumas Laboratory Compacted Samples.

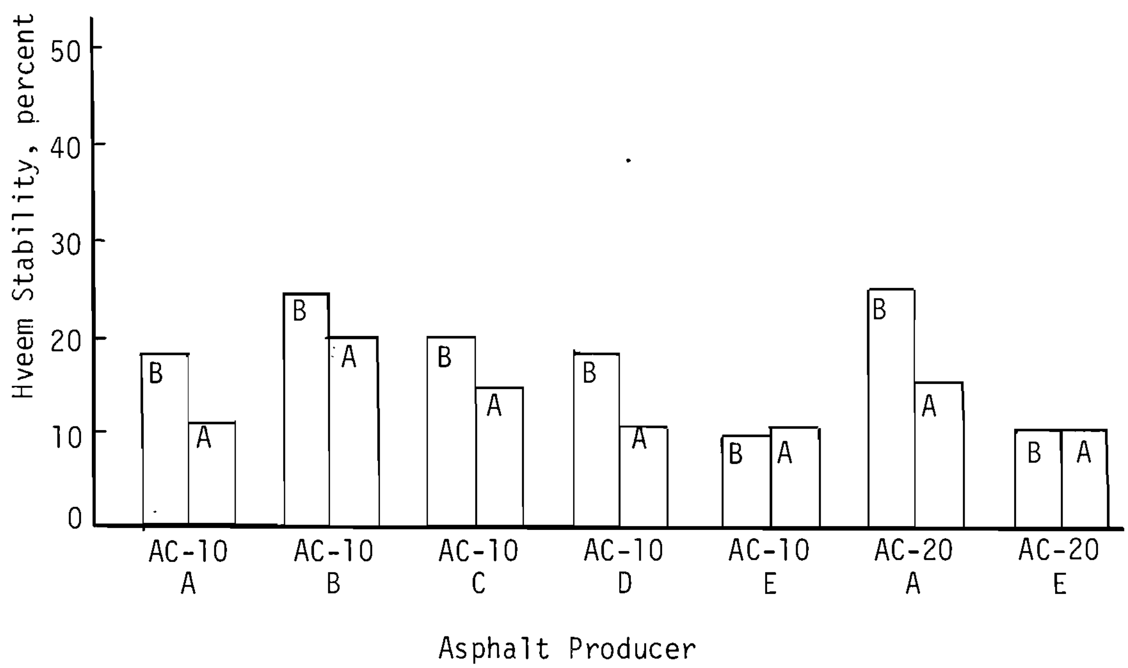

Figure 45b. Hveem Stability Before and After Lottman for Dumas One Week Cores.

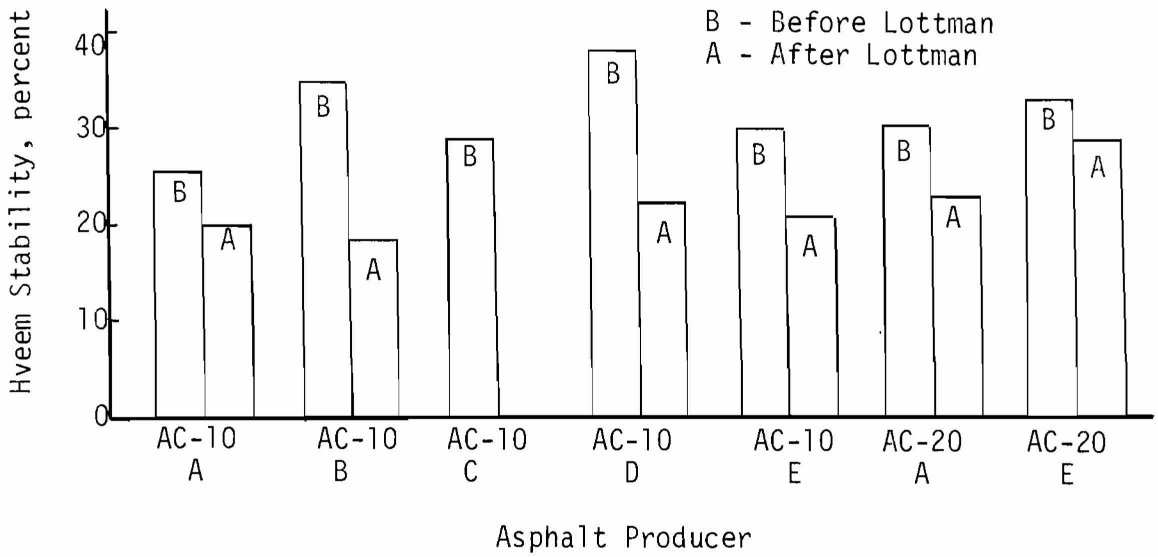

Figure 46a. Hveem Stability Before and After Lottman for Dumas One Year Cores.

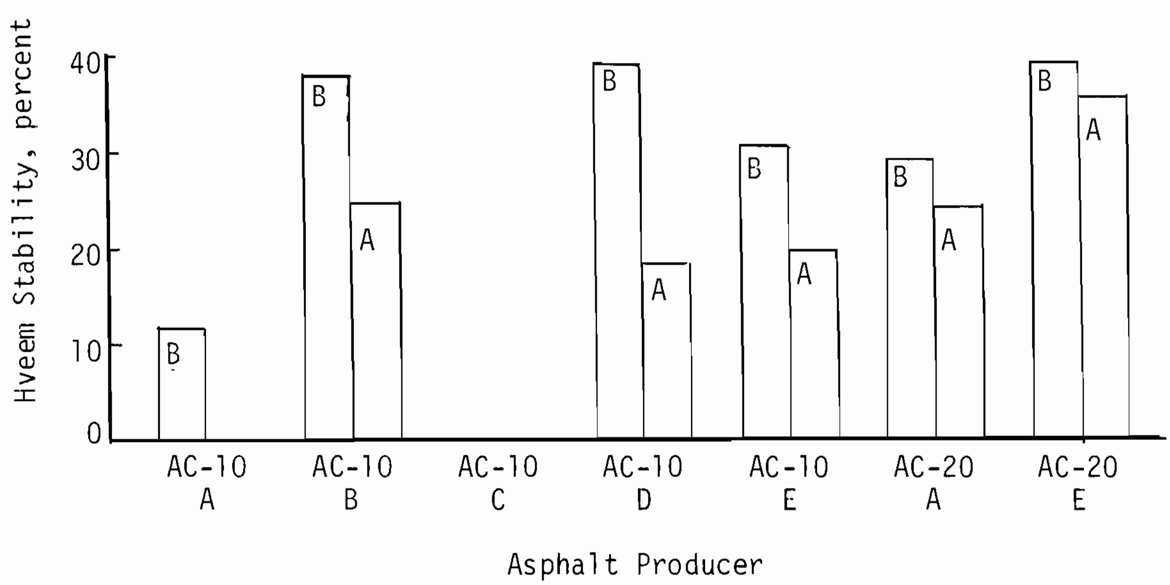

Figure 46b. Hveem Stability Before and After Lottman for Dumas Two Year Cores.

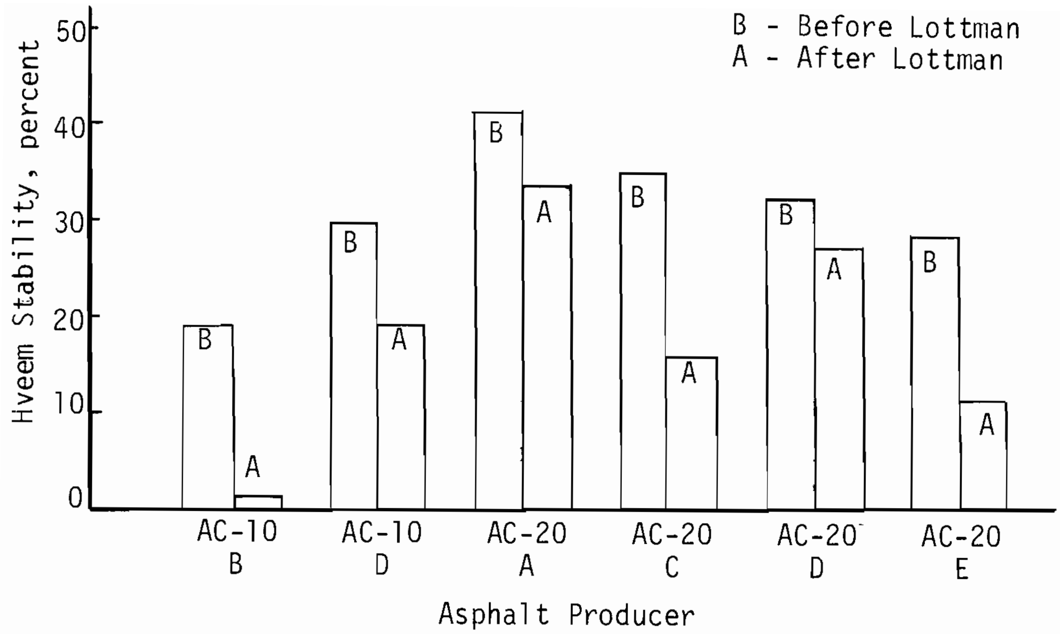

Figure 47a. Hveem Stability Before and After Lottman for Lufkin Laboratory Compacted Samples.

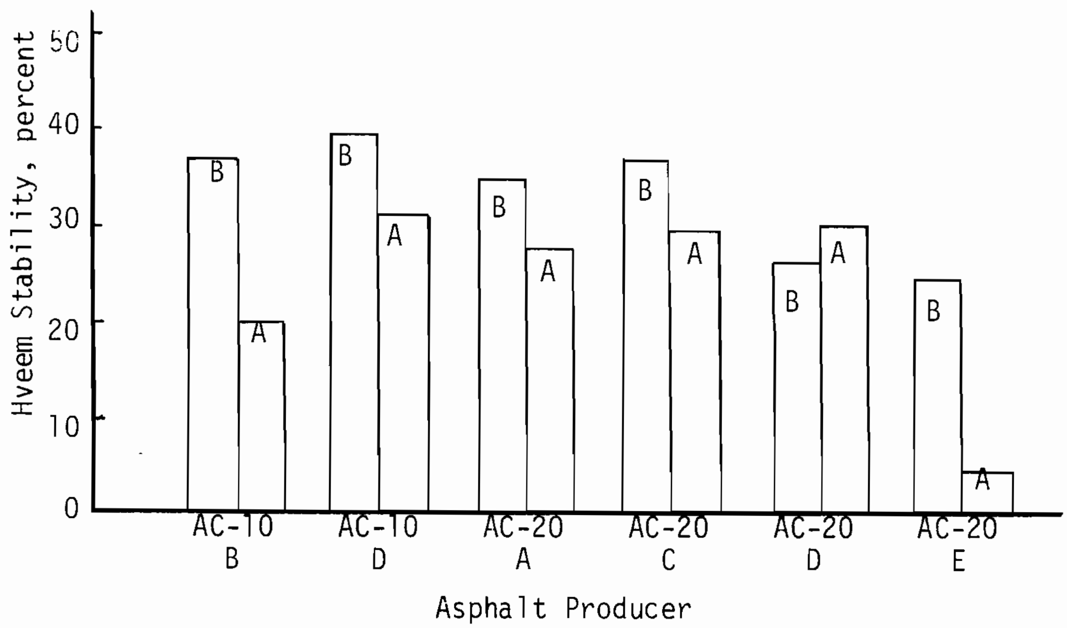

Figure 47b. Hveem Stability Before and After Lottman for Lufkin One Week Cores.

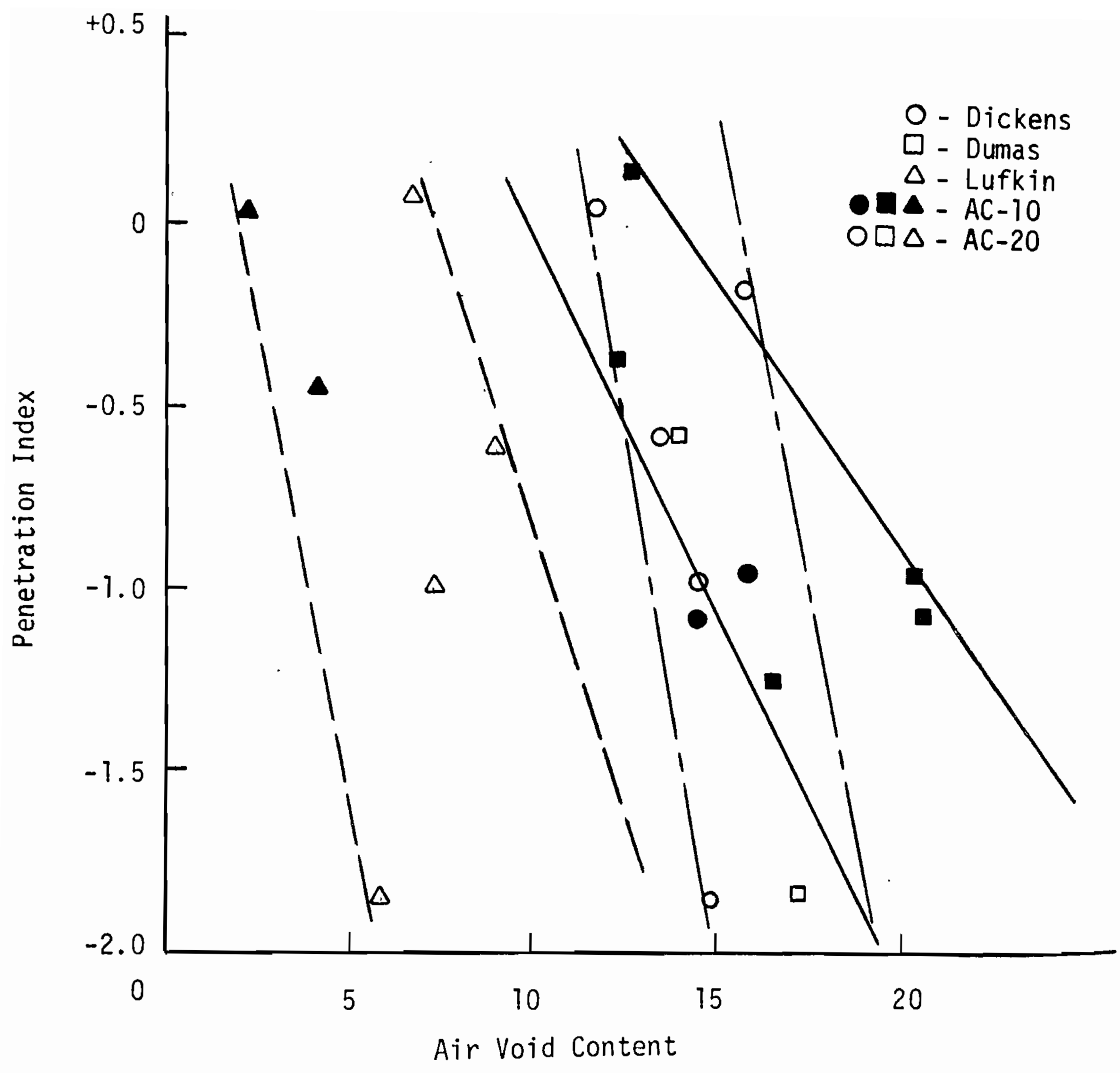

Figure 48. Relationship Between Penetration Index and Air Void Content of Pavement Cores.

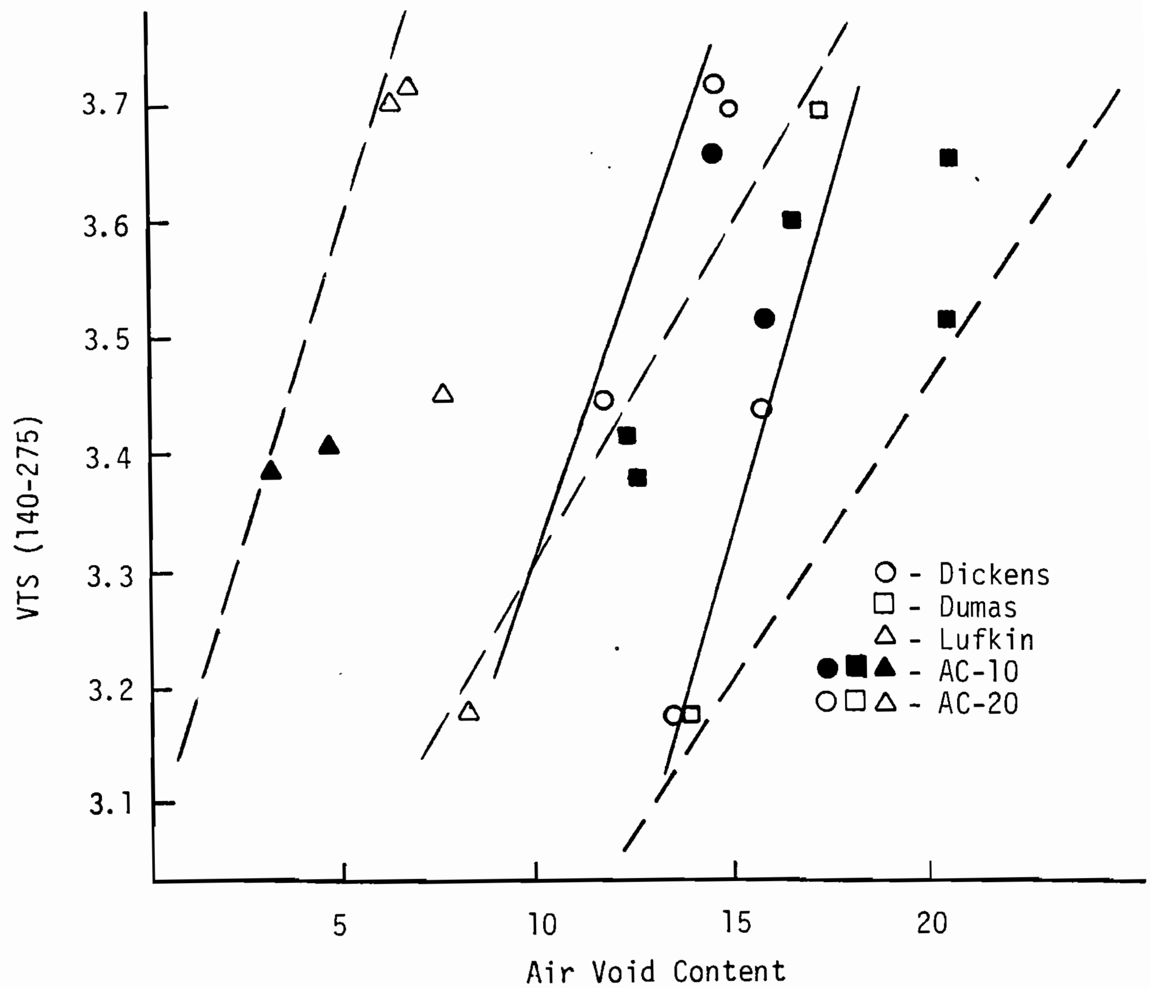

Figure 49. Relationship Between Viscosity Temperature Susceptibility and Air Void Content of Pavement Cores.

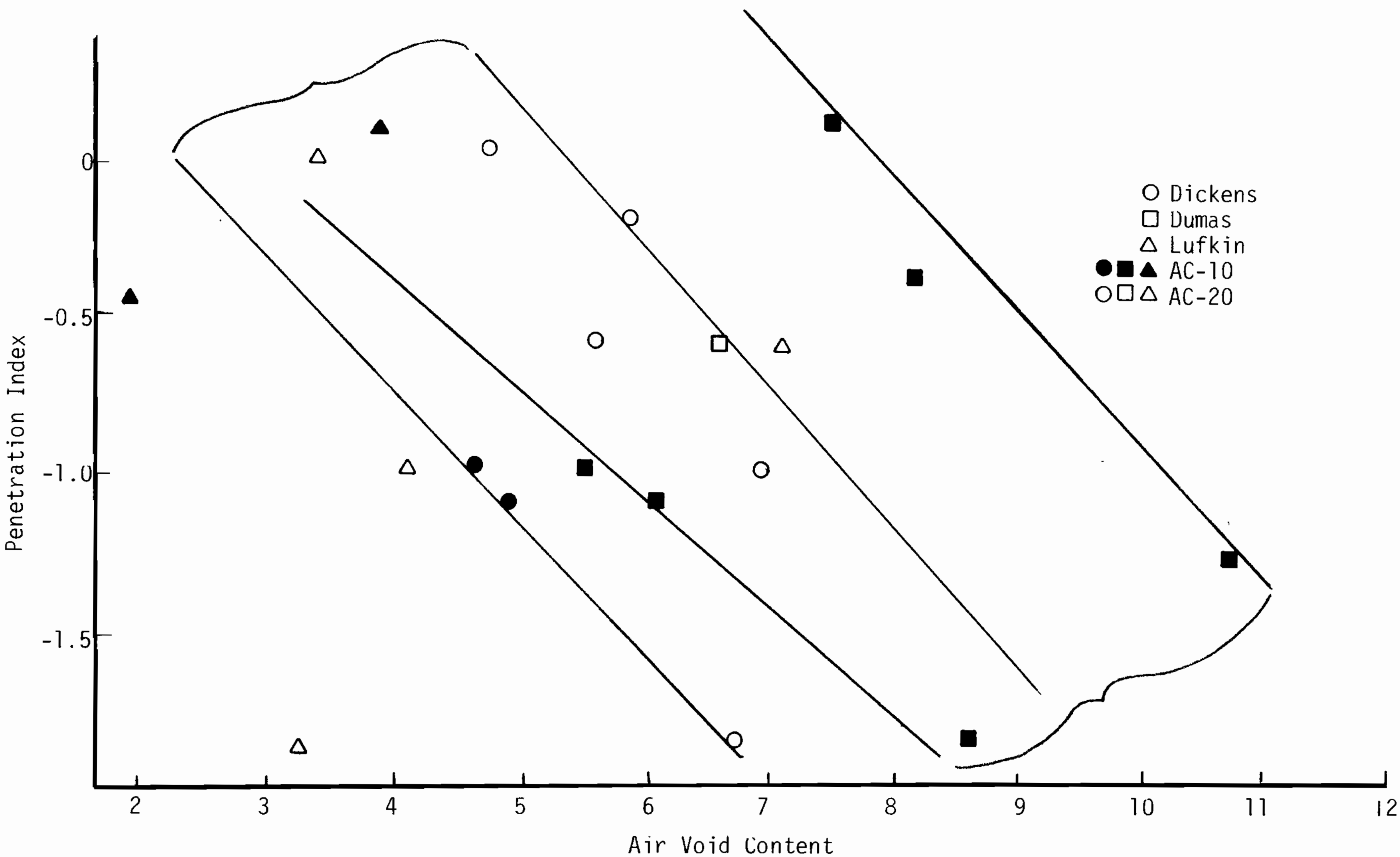

Figure 50. Air Void Content of Laboratory Compacted Specimens versus Penetration Index of Asphalt Cement.

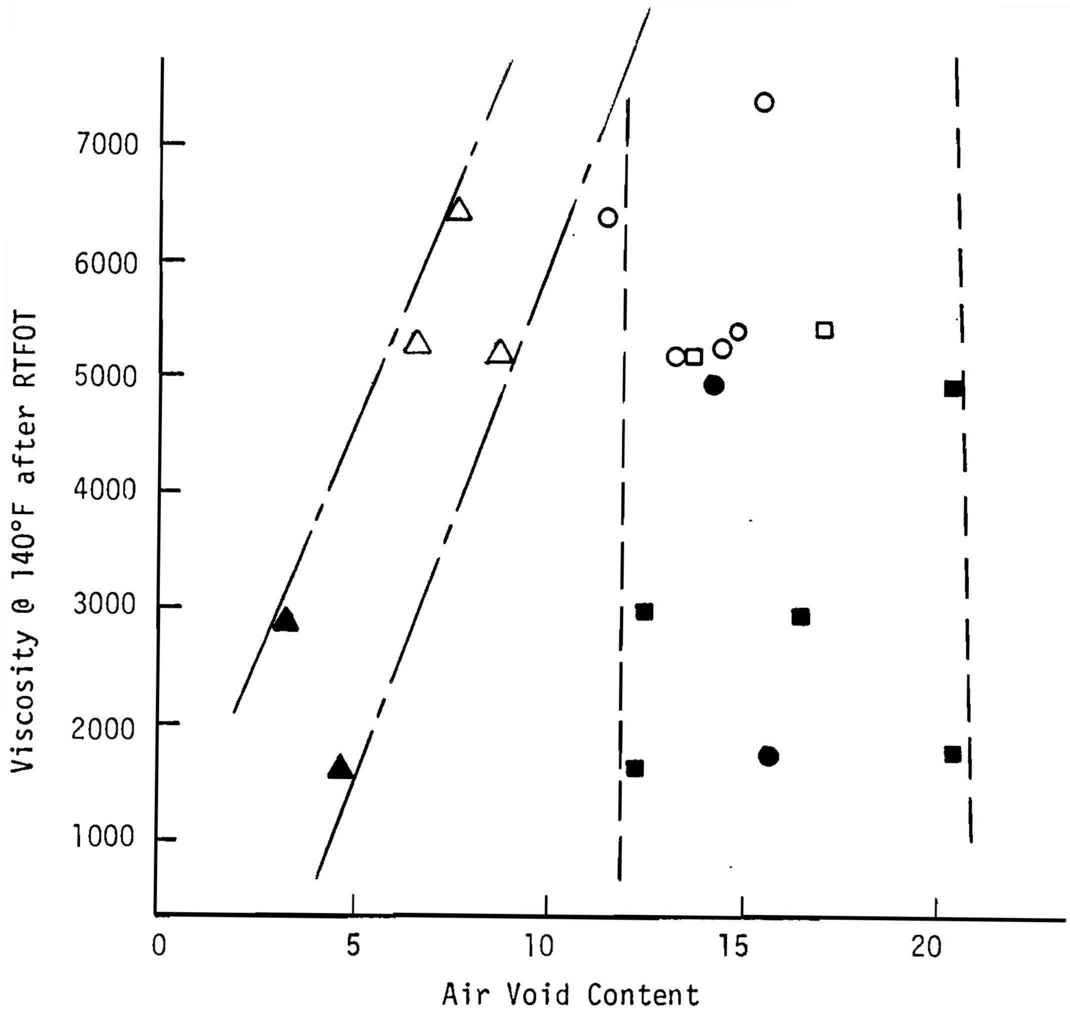

Figure 51. Relationship between Viscosity @140°F after RTFOT and Air Void Content of Pavement Cores.

content of compacted mixtures does exist, it is due to some asphalt property other than consistency.

Figure 52 also shows that air void content is not largely dependent upon asphalt viscosity as one might expect when all other variables are held constant (that is, within the capability of field operations). Laboratory compacted field mixtures containing AC-10 often exhibited greater air voids than similar mixtures containing AC-20. The mixtures in Dumas contain greater voids than those in Dickens. Hveem stability (Figure 53) depicts the greater angularity of the aggregate used in Dumas. Hveem stability appears to be independent of asphalt viscosity within the range of those employed in this experiment. This is as anticipated since Hveem stability is much more dependent on aggregate properties than asphalt properties.

Marshall stability (Figure 54), on the other hand, is generally greater for those mixtures containg the higher viscosity asphalts (AC-20) and is only slightly greater for the more angular aggregate used in Dumas. There is no relationship between Marshall stability and temperature susceptibility. This is to be expected since the asphalt cements of a given viscosity grade possess about the same viscosity at 140^{o}F. Marshall stability would be affected to a greater extent by asphalt hardening upon heating than by asphalt temperature susceptibilty when all other variables are held constant.

Resilient modulus is quite sensitive to asphalt viscosity, as illustrated in Figure 55. The mixtures containing AC-20 exhibit significantly greater resilient moduli than similar mixtures containing AC-10. Tensile strength at 77^{o}F (Figure 56) shows a relationship similar to that shown by resilient modulus. In fact, Figure 57 shows a correlation between resilient modulus and tensile strength of the field mixed and laboratory compacted mixtures. It follows then that those mixtures containing asphalts with higher temperature susceptibility and/or greater hardening upon heating will produce mixtures with larger resilient moduli and tensile strength at 77^{o}F. Now if penetration graded asphalts were used (which are graded at 77^{o}F), resilient modulus and

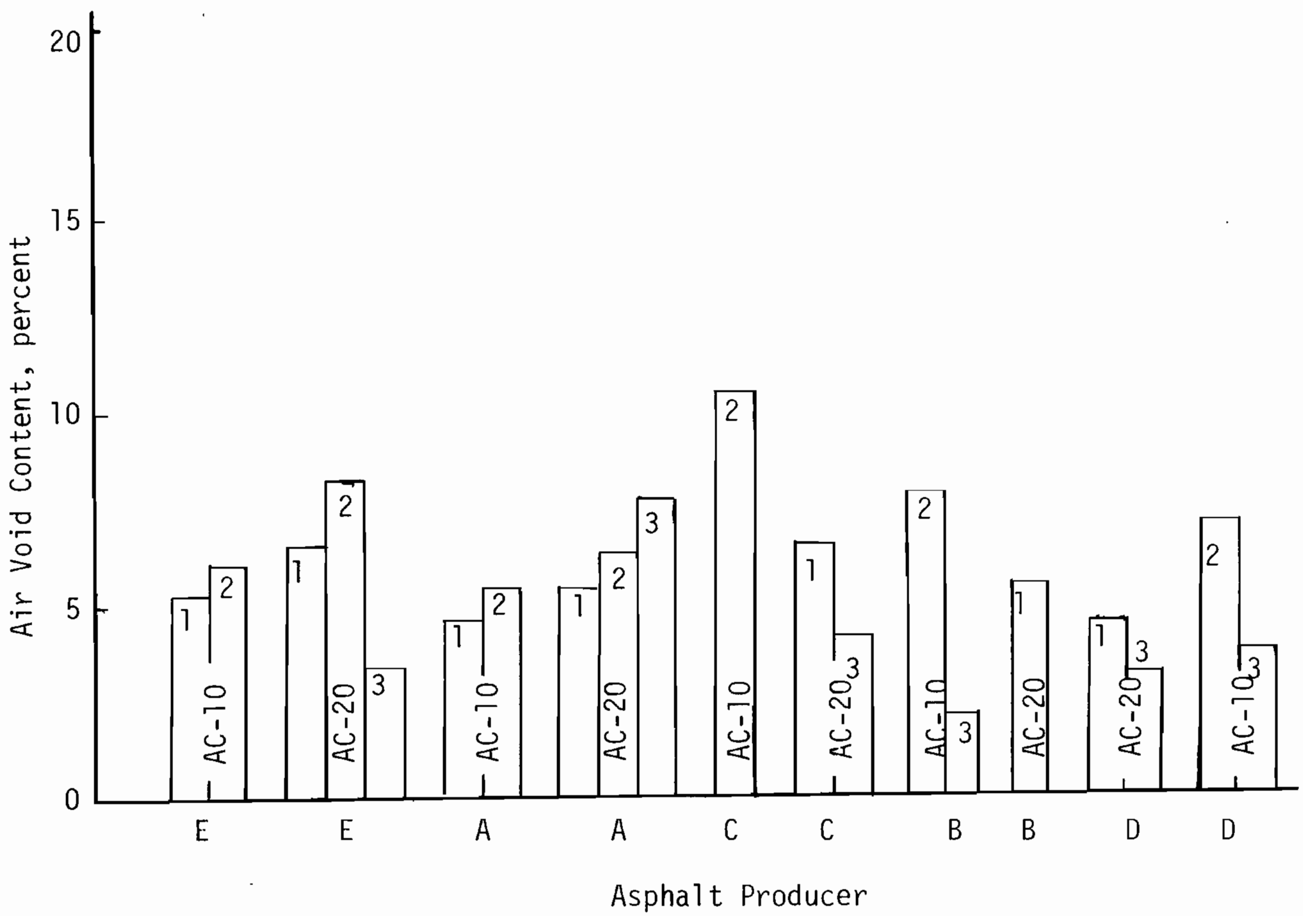

Figure 52. Air Void Content of Laboratory Molded Specimens from Dickens(1), Dumas(2), and Lufkin(3).

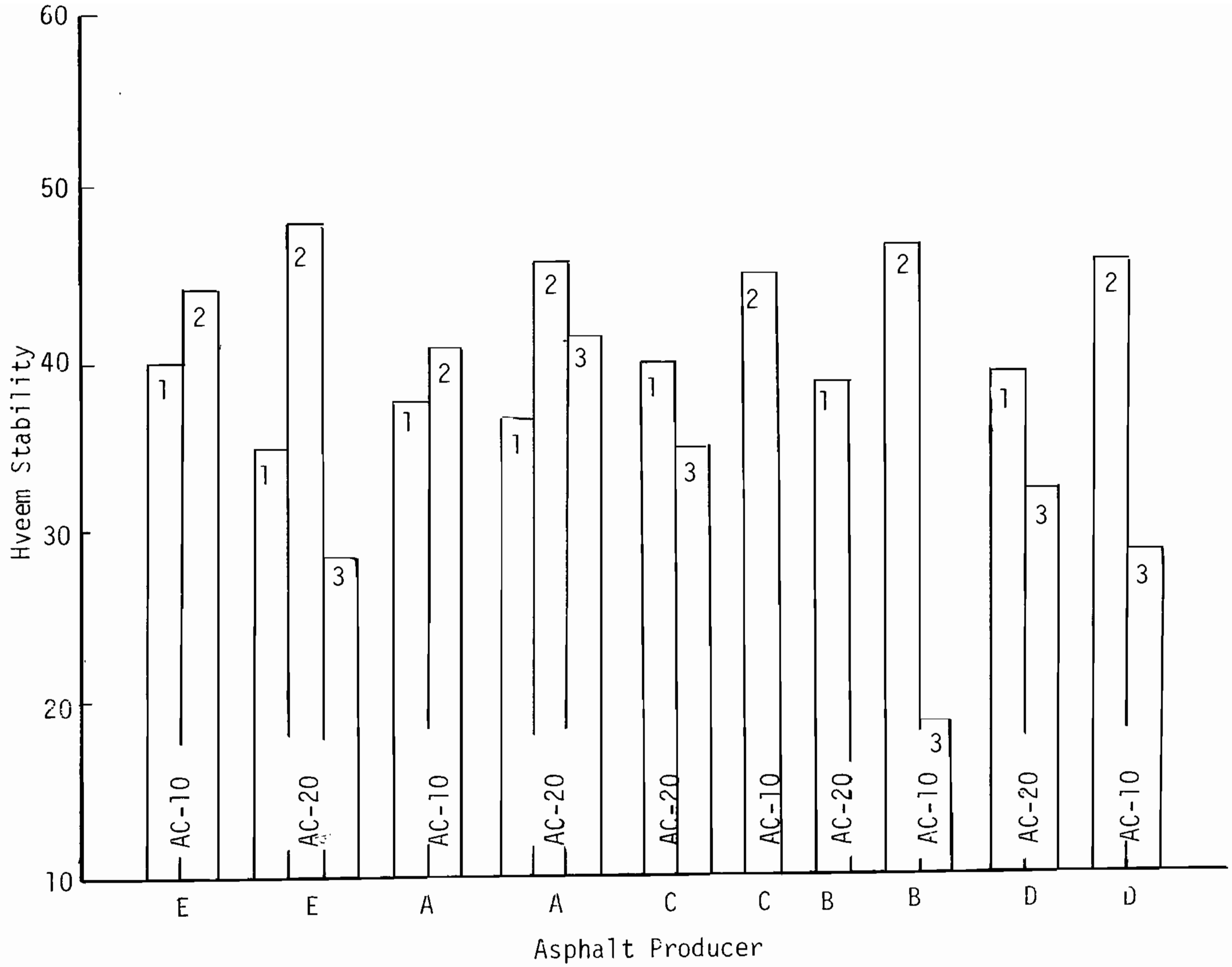

Figure 53. Hveem Stability of Laboratory Molded Specimens from Dickens(1), Dumas(2), and Lufkin(3).

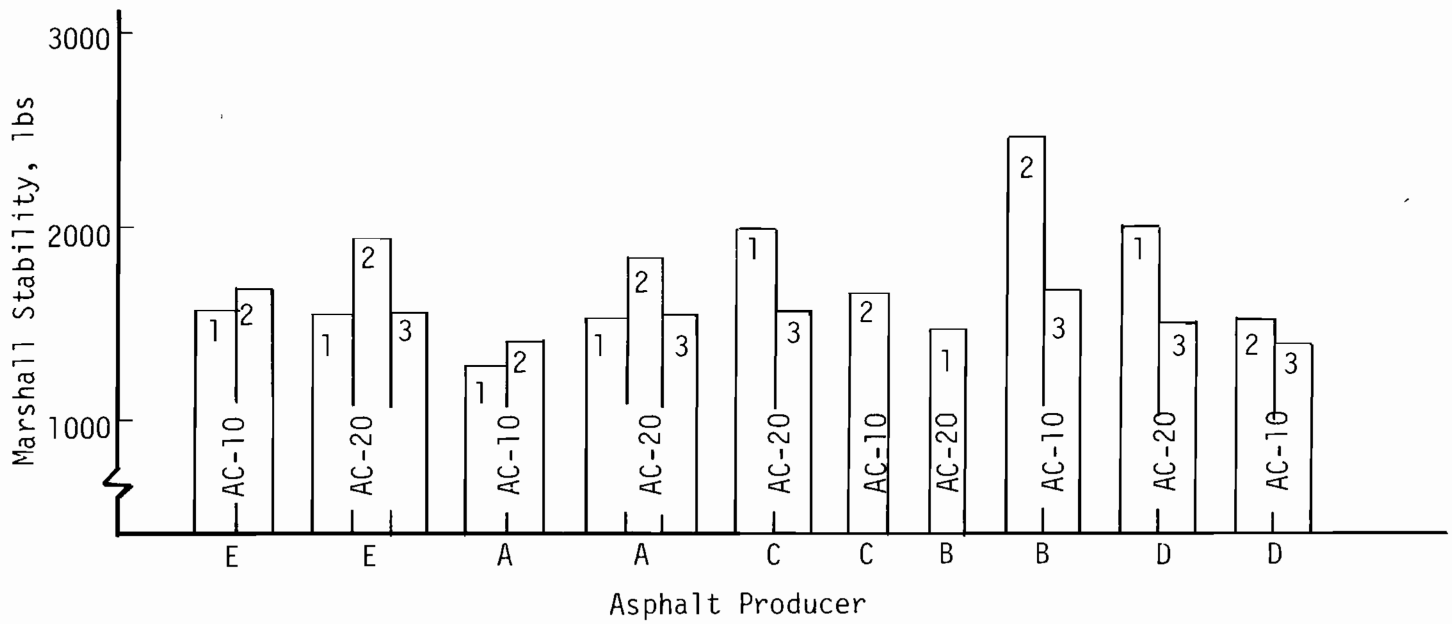

Figure 54. Marshall Stability of Laboratory Molded Specimens from Dickens(1), Dumas(2) and Lufkin(3).

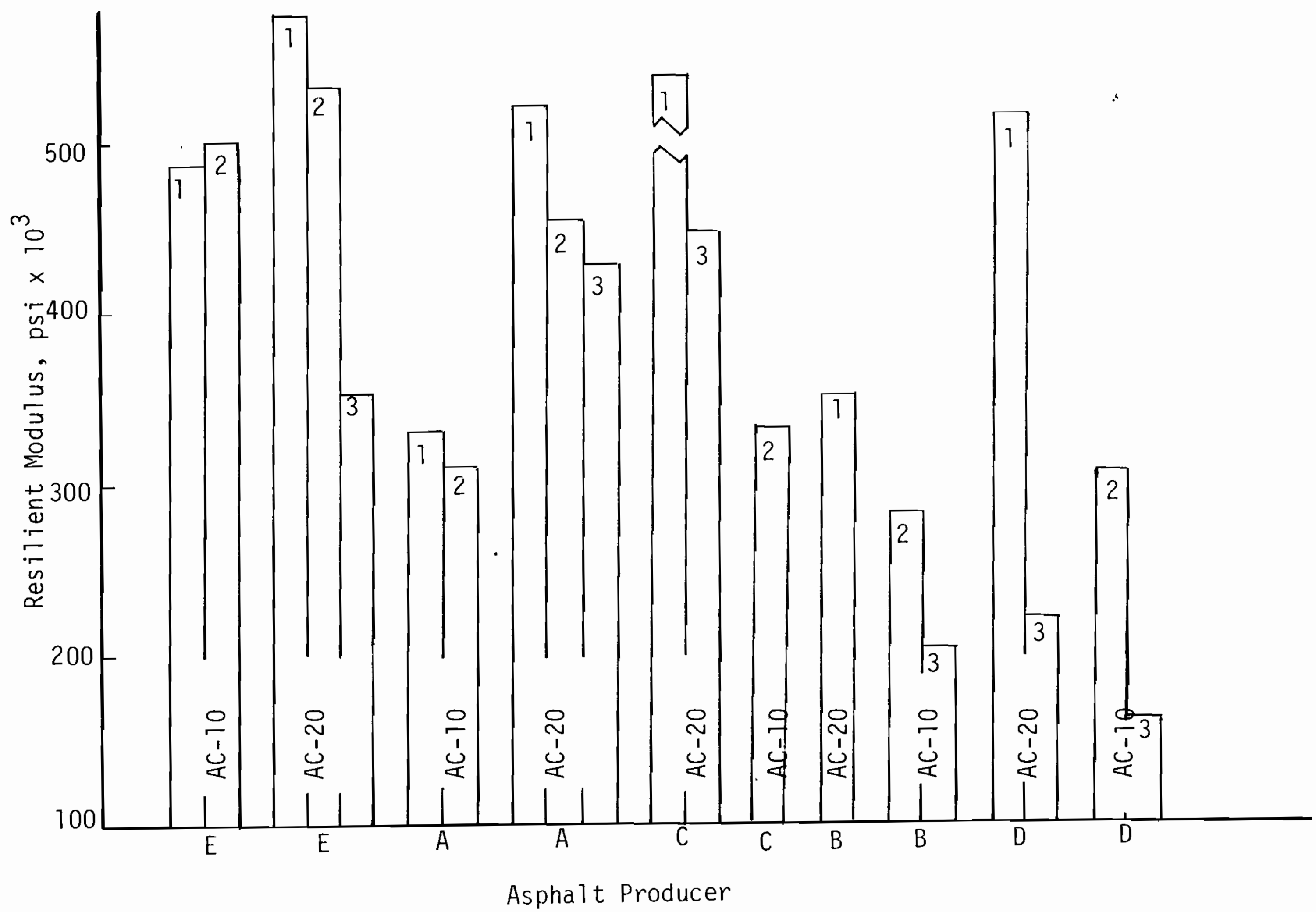

Figure 55. Resilient Modulus at 77°F of Laboratory Molded Specimens from Dickens(1), Dumas(2) and Lufkin(3).

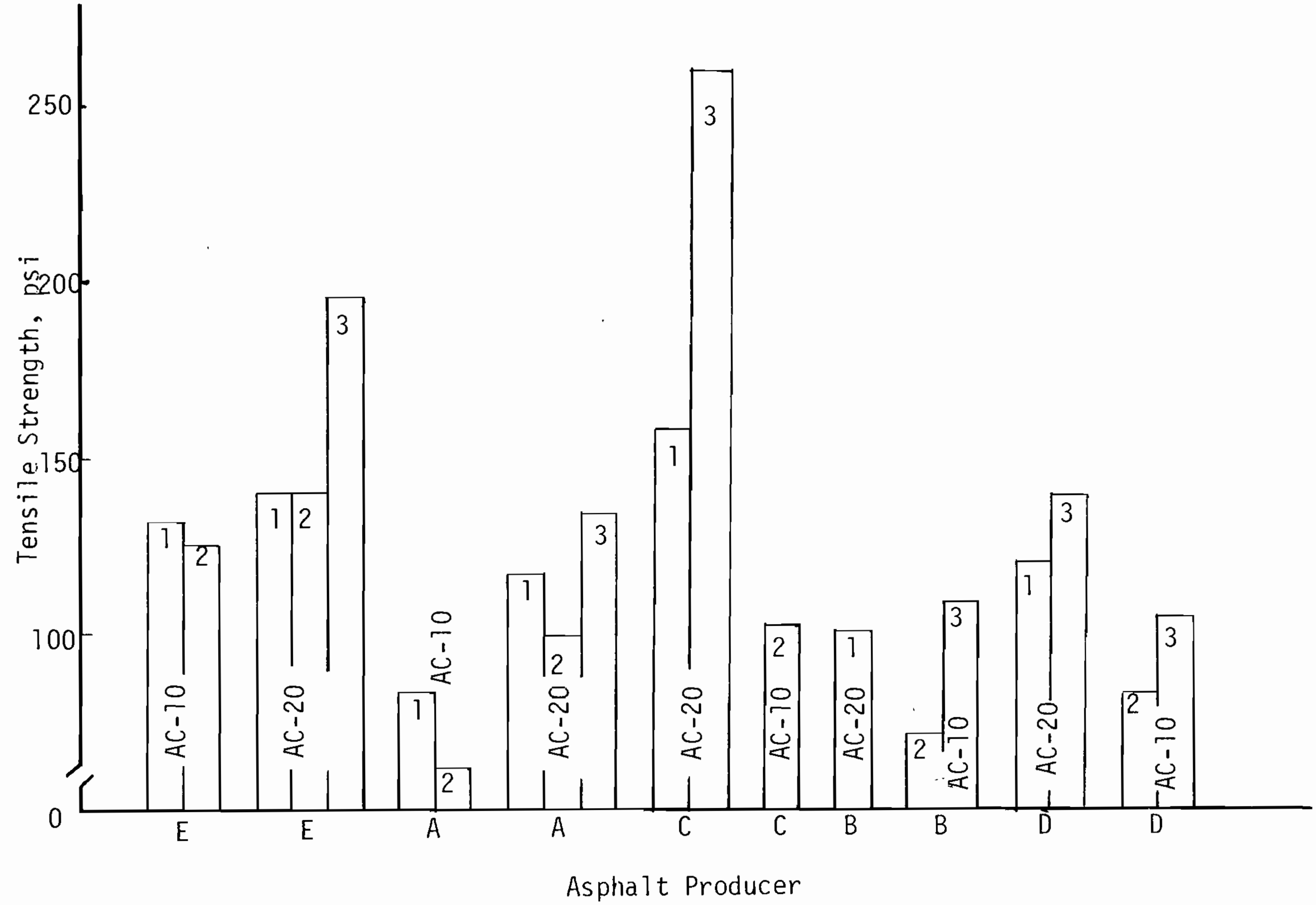

Figure 56. Tensile Strength at 77°F of Laboratory Molded Specimens from Dickens(1), Dumas(2) and Lufkin(3).

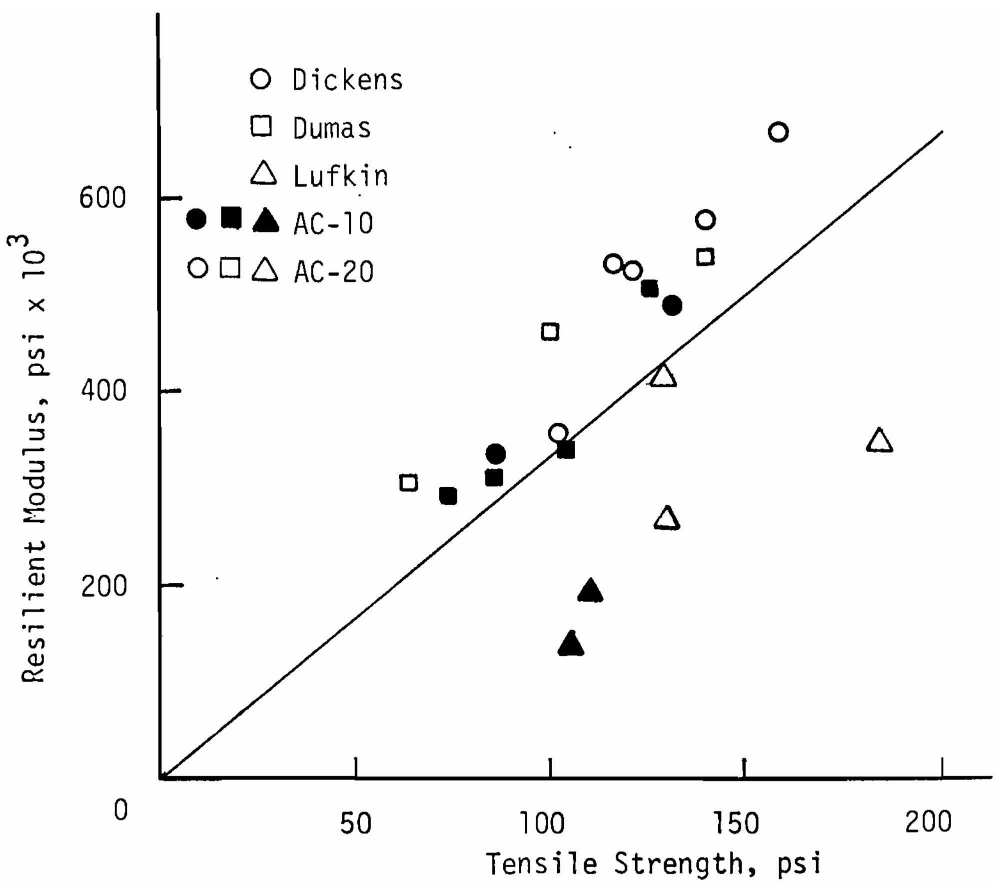

Figure 57. Resilient Modulus @ 77°F versus Tensile Strength @ 77°F for Field Mixed/Laboratory Compacted Specimens.

tensile strength at $77^{o}F$ would theoretically be independent of that asphalt's temperature susceptibility. Comparison of Figure 55 with Figure 52 shows that resilient modulus is also dependent upon air void content.

Properties of asphalts extracted and recovered from plant mixtures are given in Appendix B. These data indicate that less hardening of the asphalt occurred in the Dumas plant than in the Dickens plant. It appears, therefore, that the greater probability of a tenderness problem would have also occurred in Dumas. However, no tenderness problems were reported.

Lund and Wilson (75) developed a formula to determine the difference in the actual change in asphalt viscosity during mixing and placement that predicted by the rolling thin film oven test (RTFOT):

$$C = \frac{R-A}{B-A} \times 100\%$$

where

A = Absolute viscosity of the original asphalt at $140^{o}F$,

B = Absolute viscosity of the RTFOT residue at $140^{o}F$ and

R = Absolute viscosity of the asphalt recovered from the paving mixture at $140^{o}F$.

When C equals 100 percent, RTFOT accurately predicts the actual viscosity increase that occurs in the plant. When C is less than 100 percent, less hardening occured in the plant than that predicted by RTFOT and visa versa. The authors further stated that based on field observations of paving projects, no tenderness problems were experienced when "C" values ranged from 30 to 50 percent, and tenderness problems were always experienced when "C" values were less than 30 percent.

C-values were calculated for the projects (Table 18). The C-values vividly illustrate that less hardening occurred in the Dumas plant. Although selected C-values are less than 30 percent, no tenderness problems were observed at the Dumas project site. This indicates that

Table 18. C-Values for Dickens and Dumas Asphalts/Plants.

Location	Refinery Code	Asphalt Grade	C-Value, percent
Dickens	E	AC-10	86
	E	AC-20	83
	A	AC-10	149
	A	AC-20	249
	C	AC-20	206
	B	AC-20	190
	D	AC-20	209
Dumas	E	AC-10	49
	E	AC-20	13
	A	AC-10	109
	A	AC-20	25
	C	AC-10	105
	B	AC-10	70
	D	AC-10	55

when aggregate type and gradation are adequate, soft asphalts can be accommodated in a paving mixture.

Chapter VI

Presentation and Analysis of GPC Results

Gel Permeation Chromatography

GPC was performed on asphalts extracted from laboratory molded samples and field cores. Chromatograms are shown in Appendix D. All virgin asphalts received from the refinery and all virgin asphalts received at each site were tested. Chromatograms of the asphalt cements provided directly from the refineries are shown in Figures D1 through D10. Chromatograms produced for the virgin asphalt cements delivered to each site are shown for Dickens in Figures D11 through D16, for Dumas in Figures D17 through D23, and for Lufkin in Figures D33 through D38. The major objective of the GPC study was to evaluate its potential in quality monitoring applications. To meet this criterion, the test must be performed before mixing operations begin and indicate some quality parameter. However, to follow up this testing, chromatography was used on selected samples extracted from field mixtures. Chromatograms are shown for Dumas in Figures D24 through D32 and for Lufkin in Figures D39 through D47.

The first two factors to be considered were the reproducibility of the test and the effect of asphalt grade on chromatograms produced for the same refinery. The reproducibility question was addressed by testing three samples from each of two refineries. The asphalts chosen are considered to be distinctively different in many ways. Although each meets the same specification, Asphalt A has few asphaltenes and is not considered to be very temperature susceptible, while Asphalt E has a large amount of asphaltenes and is considered to be very temperature susceptible. Chromatograms of the three different samples of Asphalt A are shown in Figure 58 and those of Asphalt E are shown in Figure 59. The results indicated that, with the equipment used in this study, the test is reproducible which confirms the results of others (45, 52).

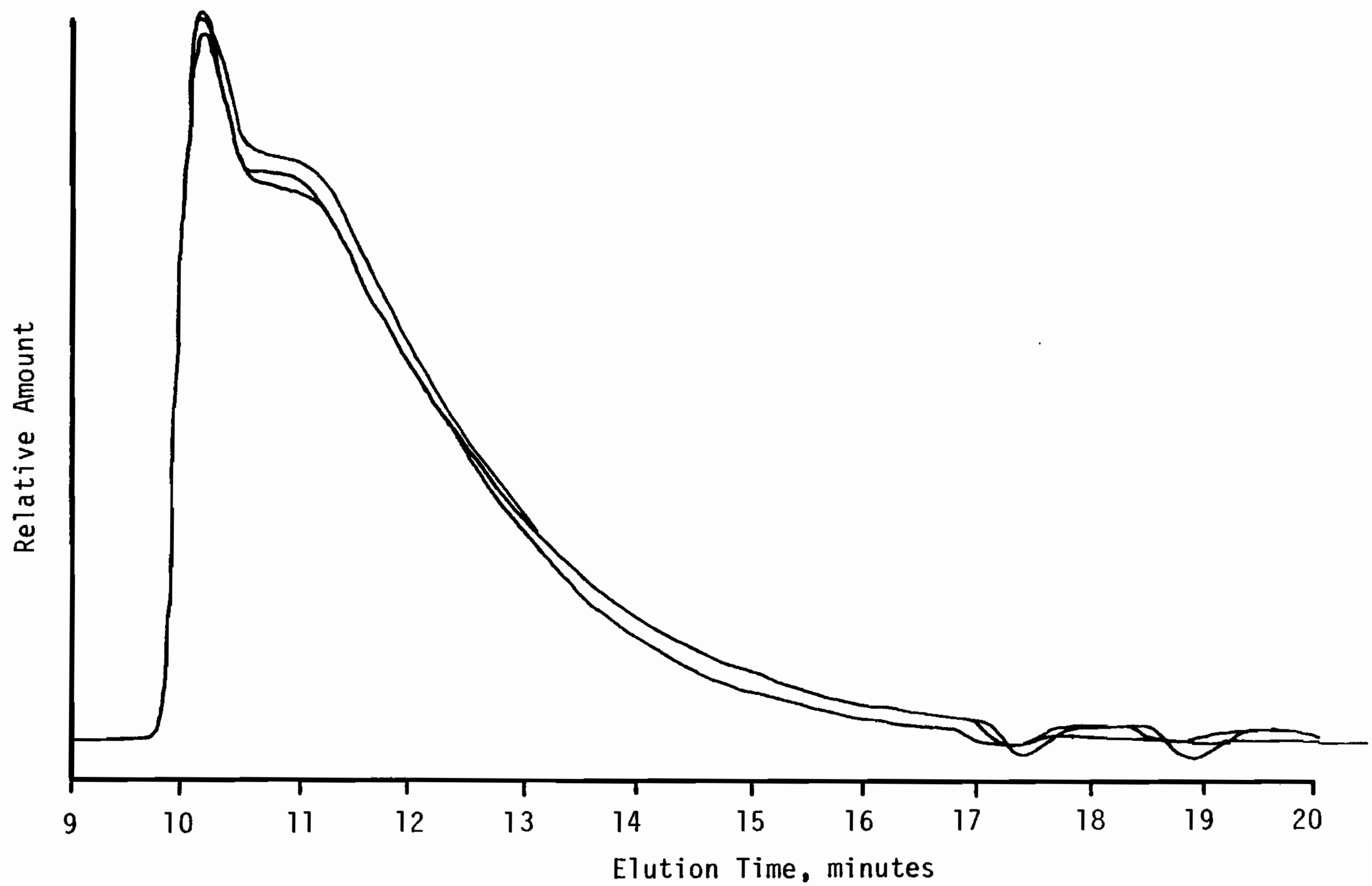

Figure 58. Three Different Test Chromatograms of the Same Sample of Asphalt A, AC-10.

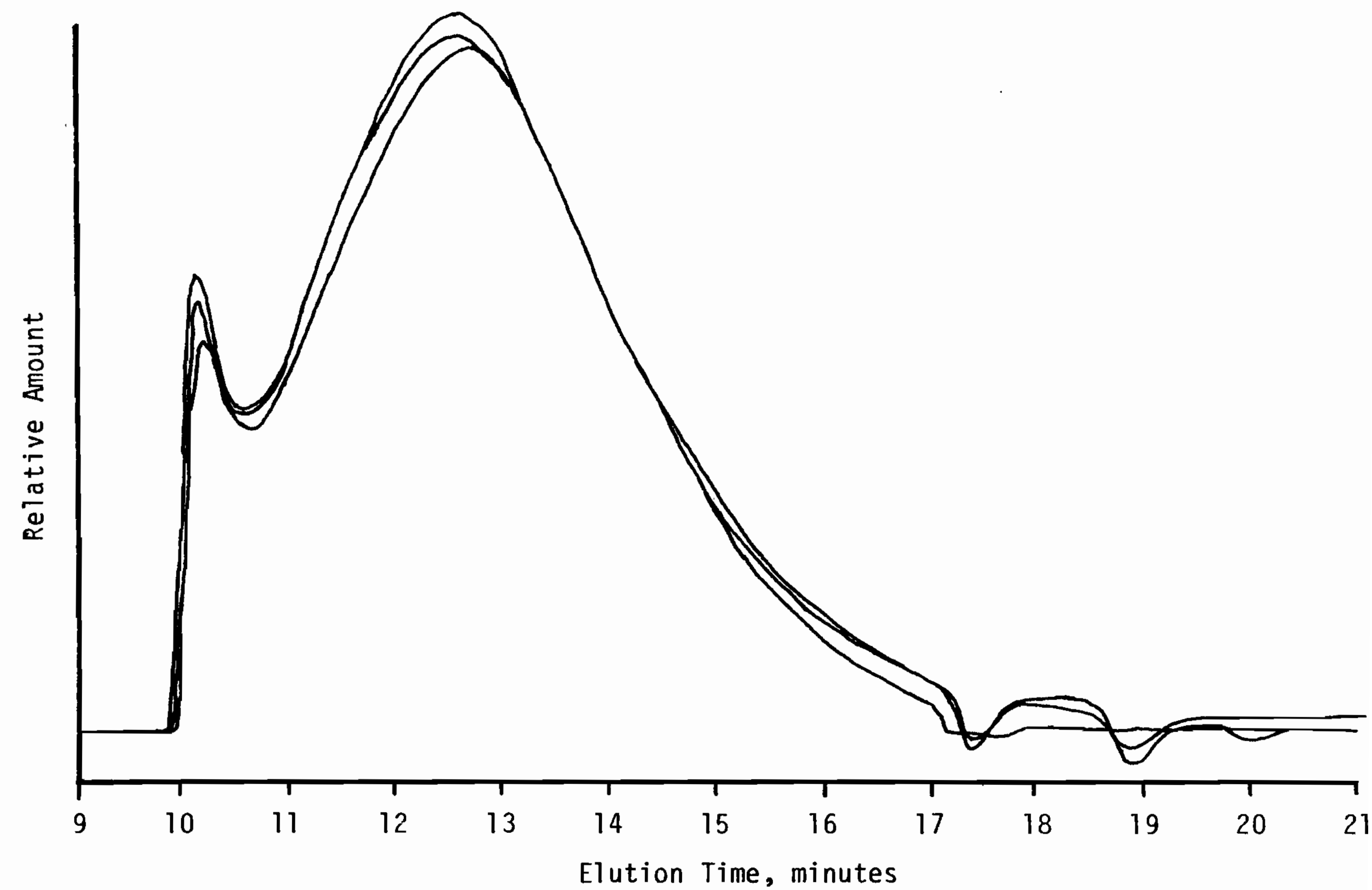

Figure 59. Three Different Test Chromatograms of the Same Sample of Asphalt E, AC-10.

The effect of grade on chromatograms was also compared for Asphalts A and E. Resulting chromatograms for Asphalt A are shown in Figure 60 and for Asphalt E in Figure 61. It is interesting to note that there are no significant differences between grades shown in the chromatograms. This was also noted by Jennings, who investigated asphalt cements used in Montana (59).

Several asphalts were common to the various project locations. Chromatograms of Asphalt A, AC-20, and Asphalt E, AC-20, shown in Figures 62 and 63, respectively, are the virgin asphalt cements from each of the three field locations. Asphalt A, AC-10, and Asphalt E, AC-10, common to Dickens and Dumas, are shown in Figures 64 and 65. Asphalts B and C, both AC-20, were common to Dickens and Lufkin and are presented in Figures 66 and 67. Asphalt D, AC-10 shown in Figure 68, was common to Dumas and Lufkin.

In addition to reproducibility and effect of grade, another aspect of the GPC in asphalt technology is determining the cause or source of certain physical properties. This would be especially valuable in reference to the emergence of asphalt additives. One such property of interest is temperature susceptibility of an asphalt cement. Two asphalts which represent the extremes in temperature susceptibility in Texas are Asphalt A and Asphalt E. The chromatograms of these asphalts are shown in Figure 69.

Hot Mixed Asphaltic Concrete Versus GPC

While the binder makes up only 4 to 7 percent by weight of the hot mixed asphaltic concrete, it does provide all the adhesive properties. This obviously can be related to the strength of the final mixture. There are, of course, many other factors that also influence strength, such as, air void content, aggregate gradation, aggregate type and asphalt content. Since it has been previously pointed out that the GPC is relatively unaffected by asphalt cement grade, three asphalts from three producers common to all three locations were evaluated regardless of grade. Asphalts A,C, and E were tested. Since the aggregates were

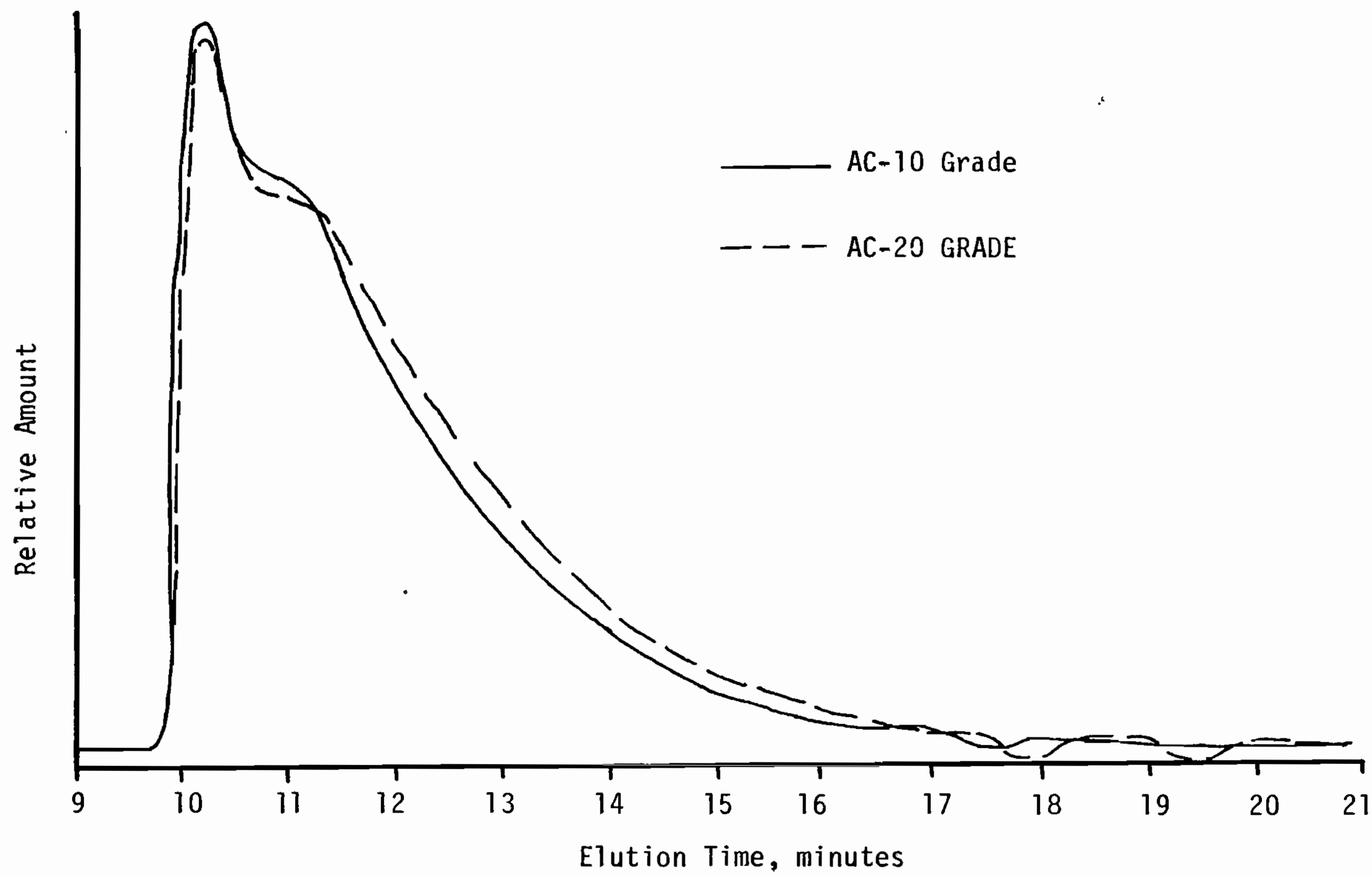

Figure 60. Chromatograms for Grades AC-10 and AC-20 for Asphalt A Received from the Producer.

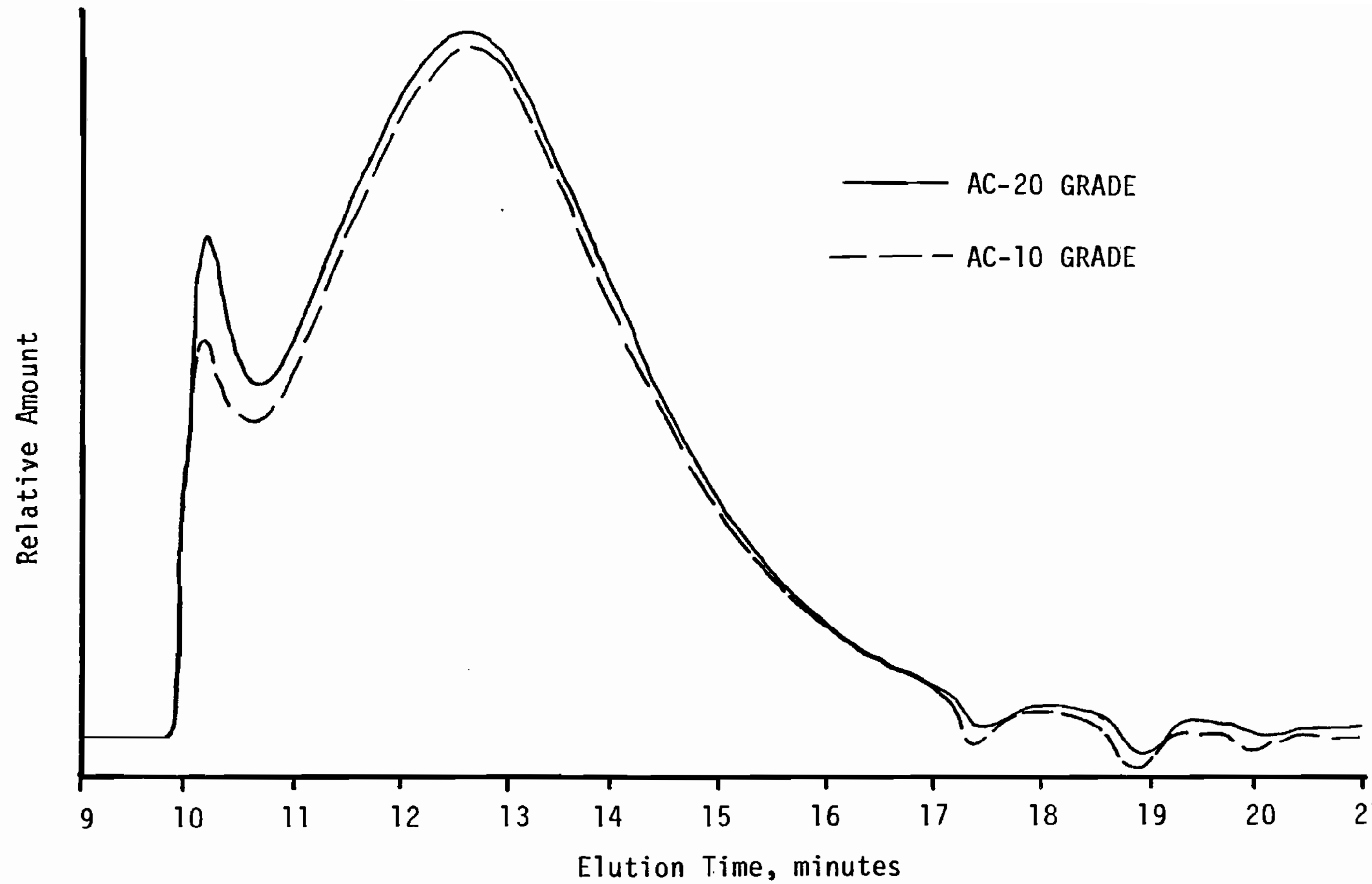

Figure 61. Chromatograms for Grades AC-10 and AC-20 for Asphalt E Received from the Producer.

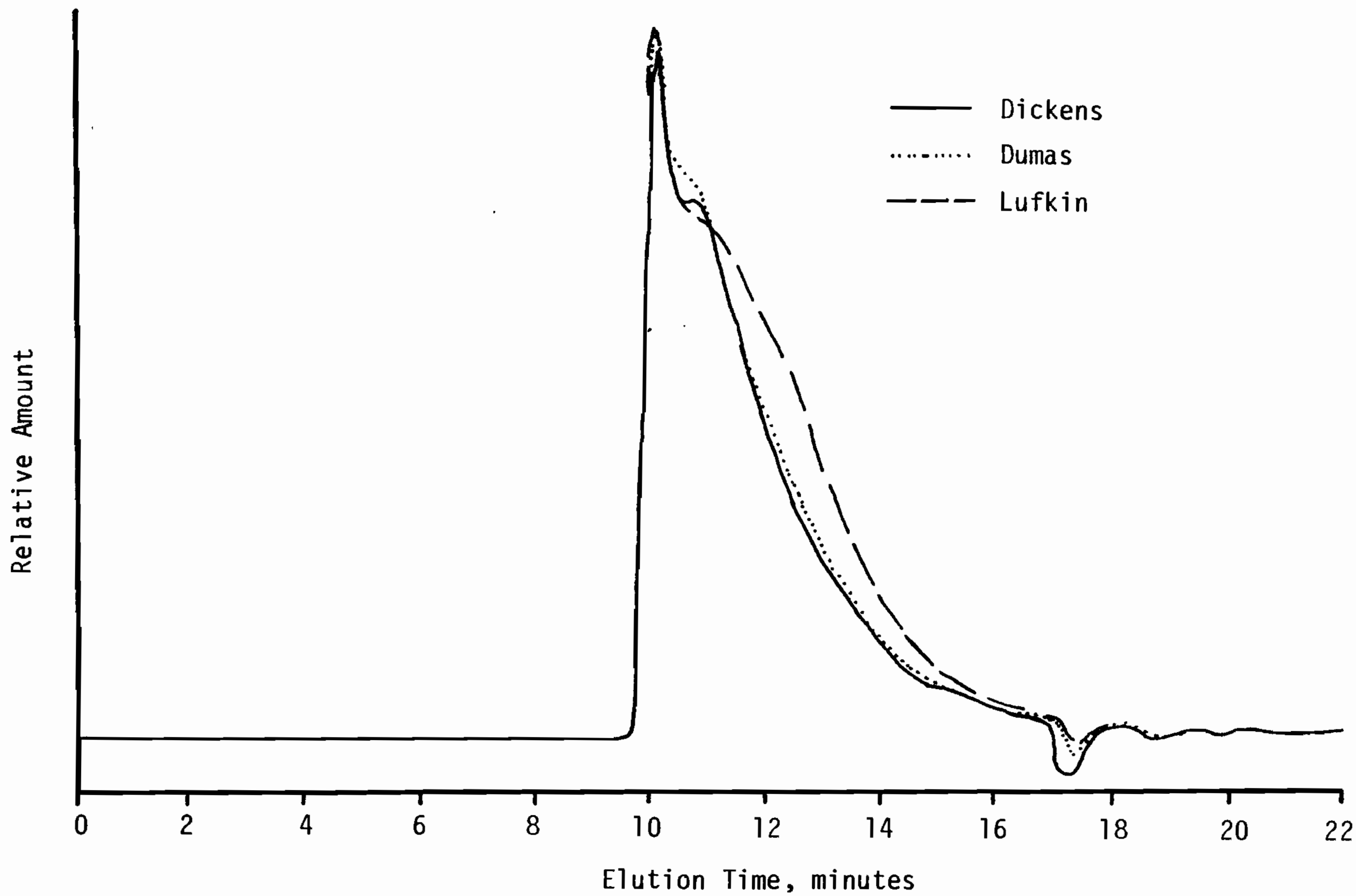

Figure 62. Chromatograms of Virgin Asphalt A, AC-20, Common to all Three Projects.

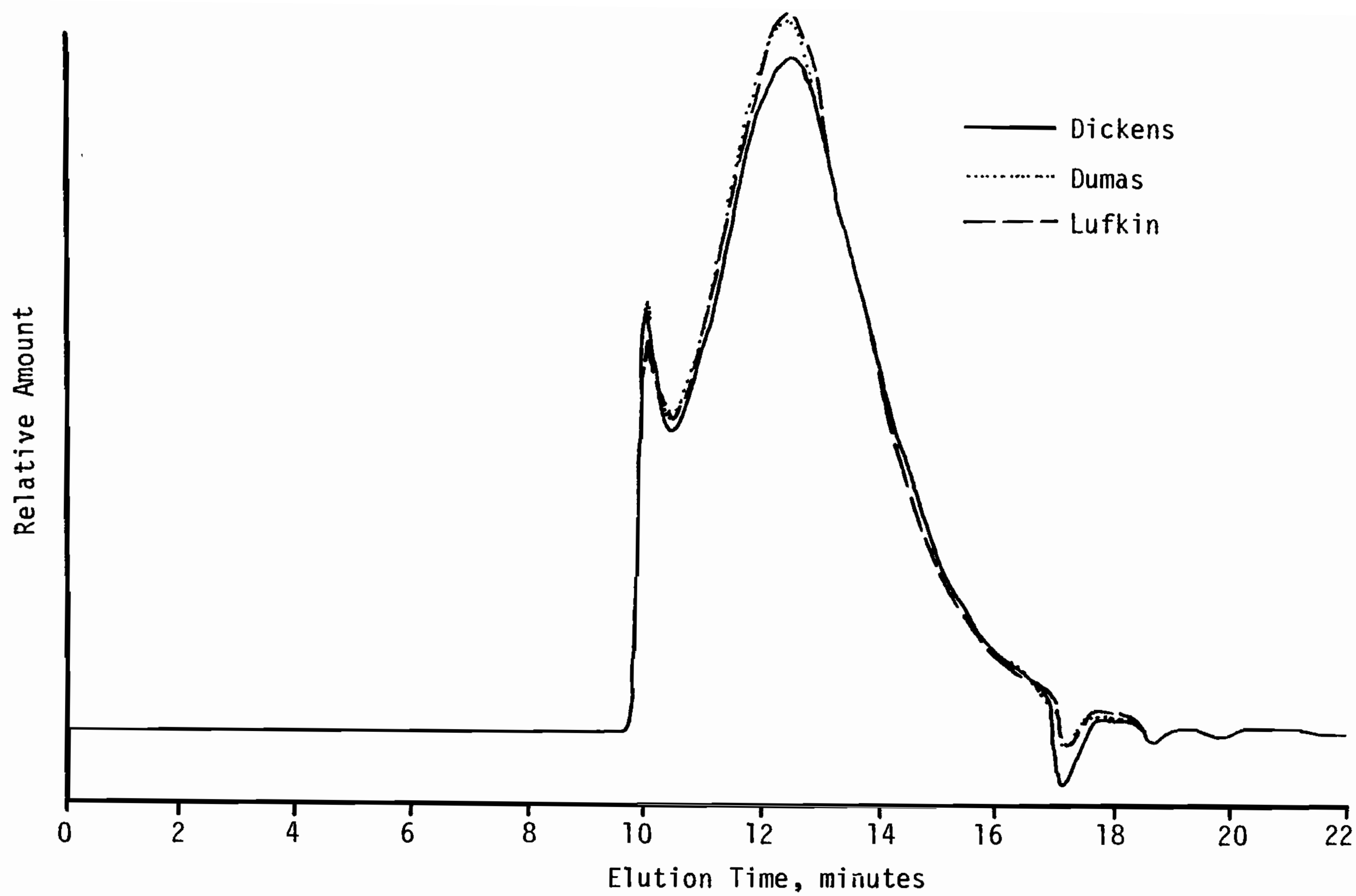

Figure 63. Chromatograms of Virgin Asphalt E, AC-20, Common to all Three Projects.

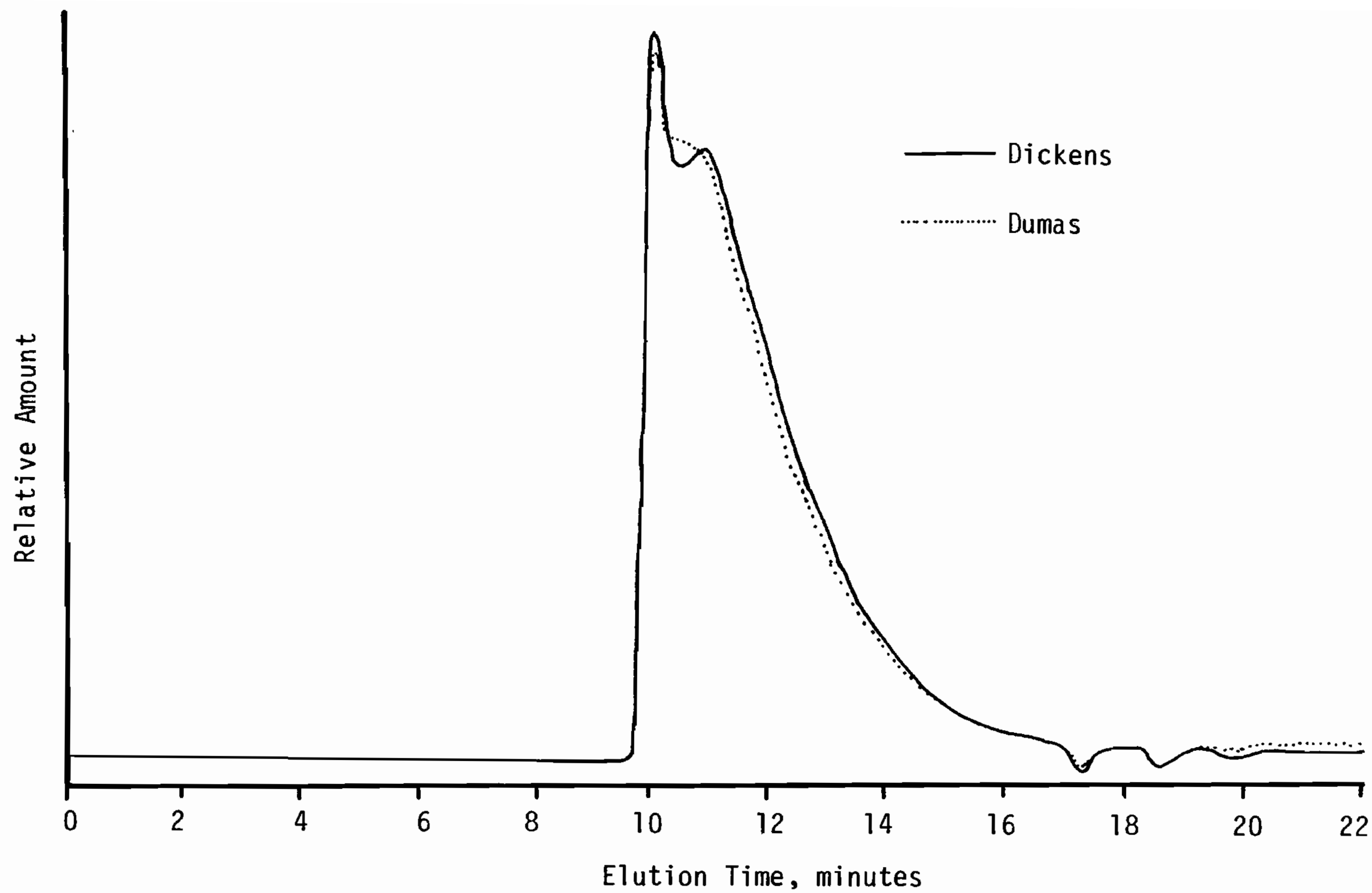

Figure 64. Chromatograms of Virgin Asphalt A, AC-10, Common to Dickens and Dumas.

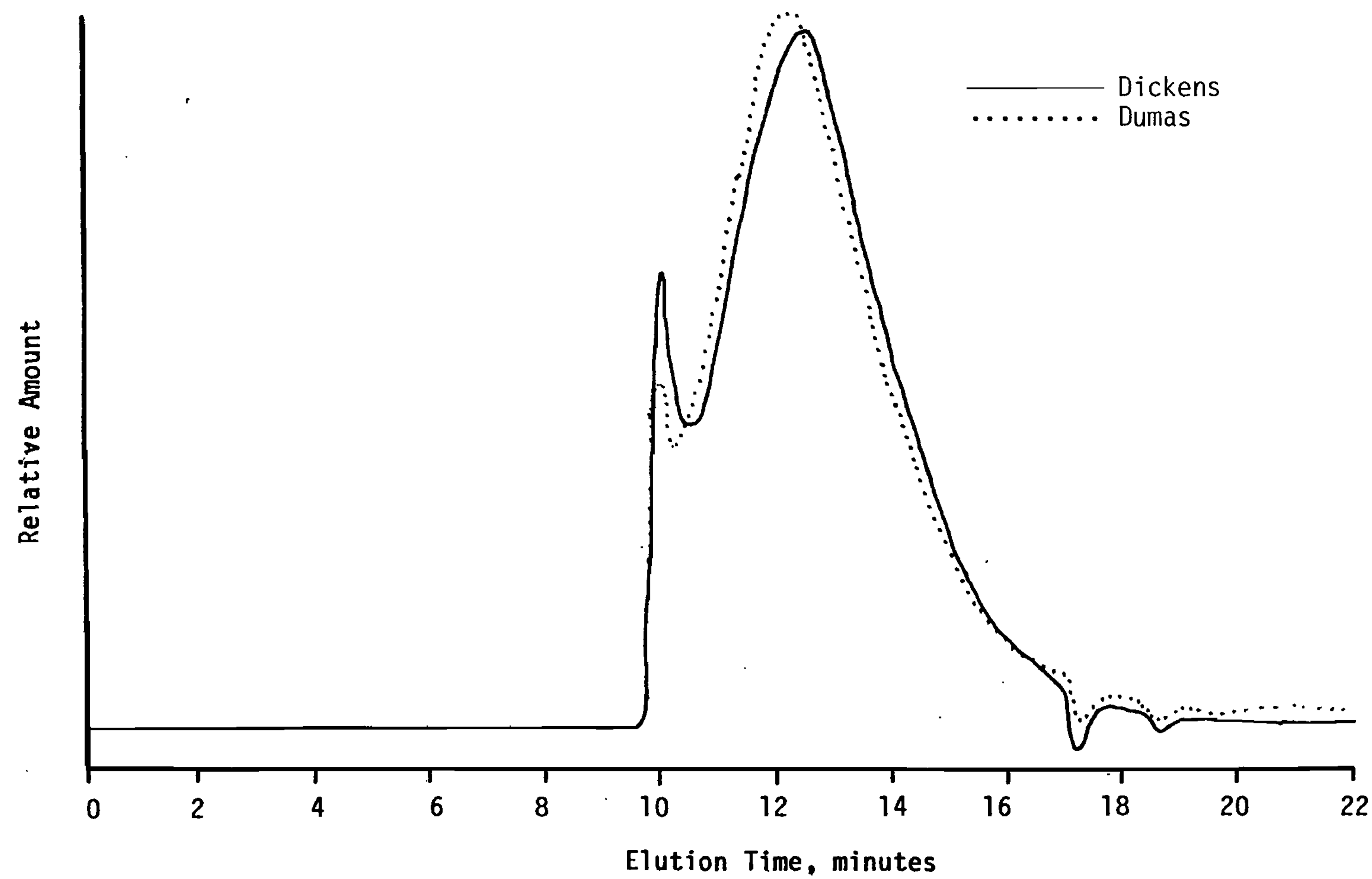

Figure 65. Chromatograms of Virgin Asphalt E, AC-10, Common to Dickens and Dumas.

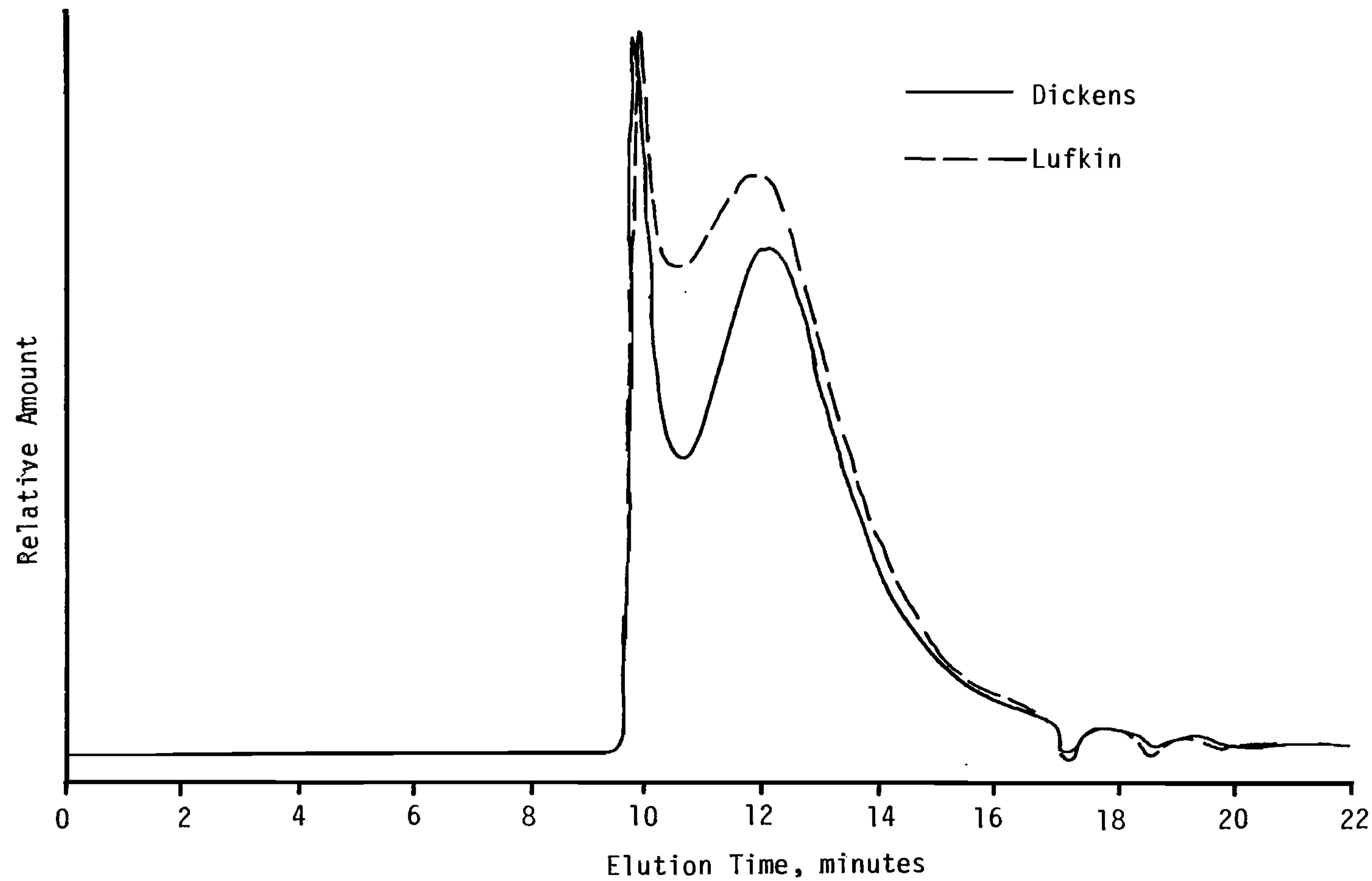

Figure 66. Chromatograms of Virgin Asphalt B, AC-20, Common to Dickens and Lufkin.

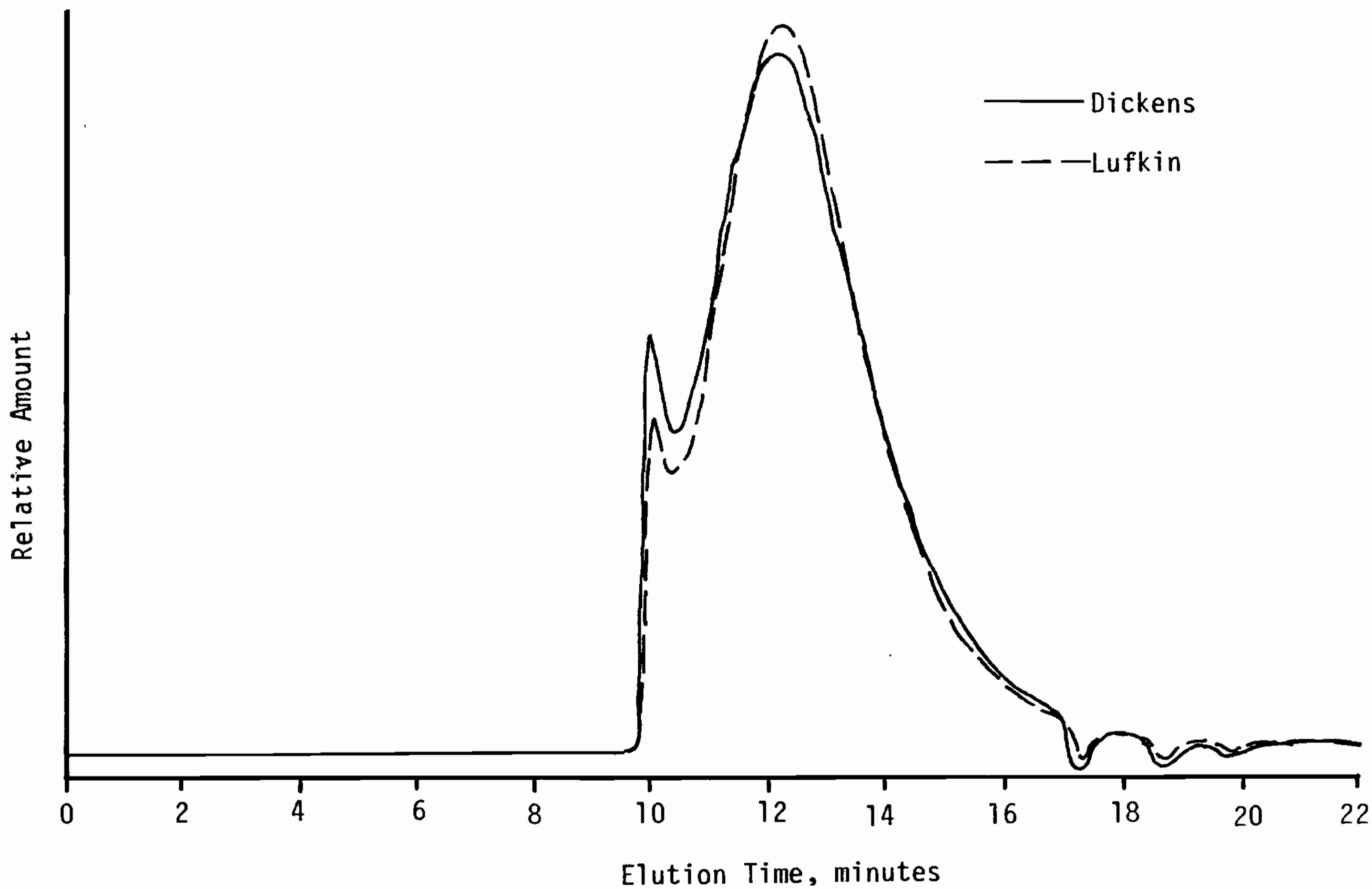

Figure 67. Chromatograms of Virgin Asphalt C, AC-20, Common to Dickens and Lufkin.

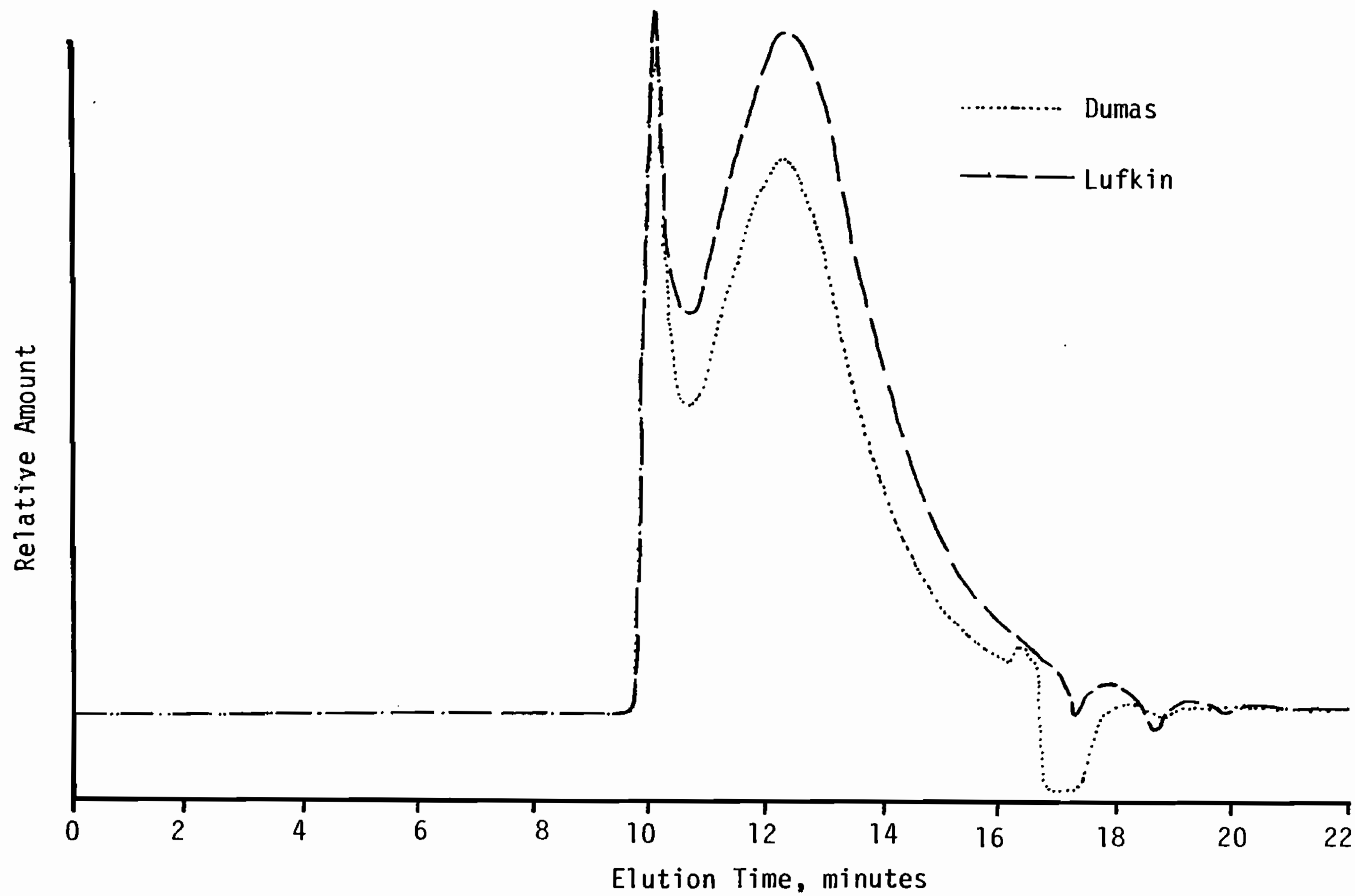

Figure 68. Chromatograms of Virgin Asphalt D, AC-10, Common to Dumas and Lufkin.

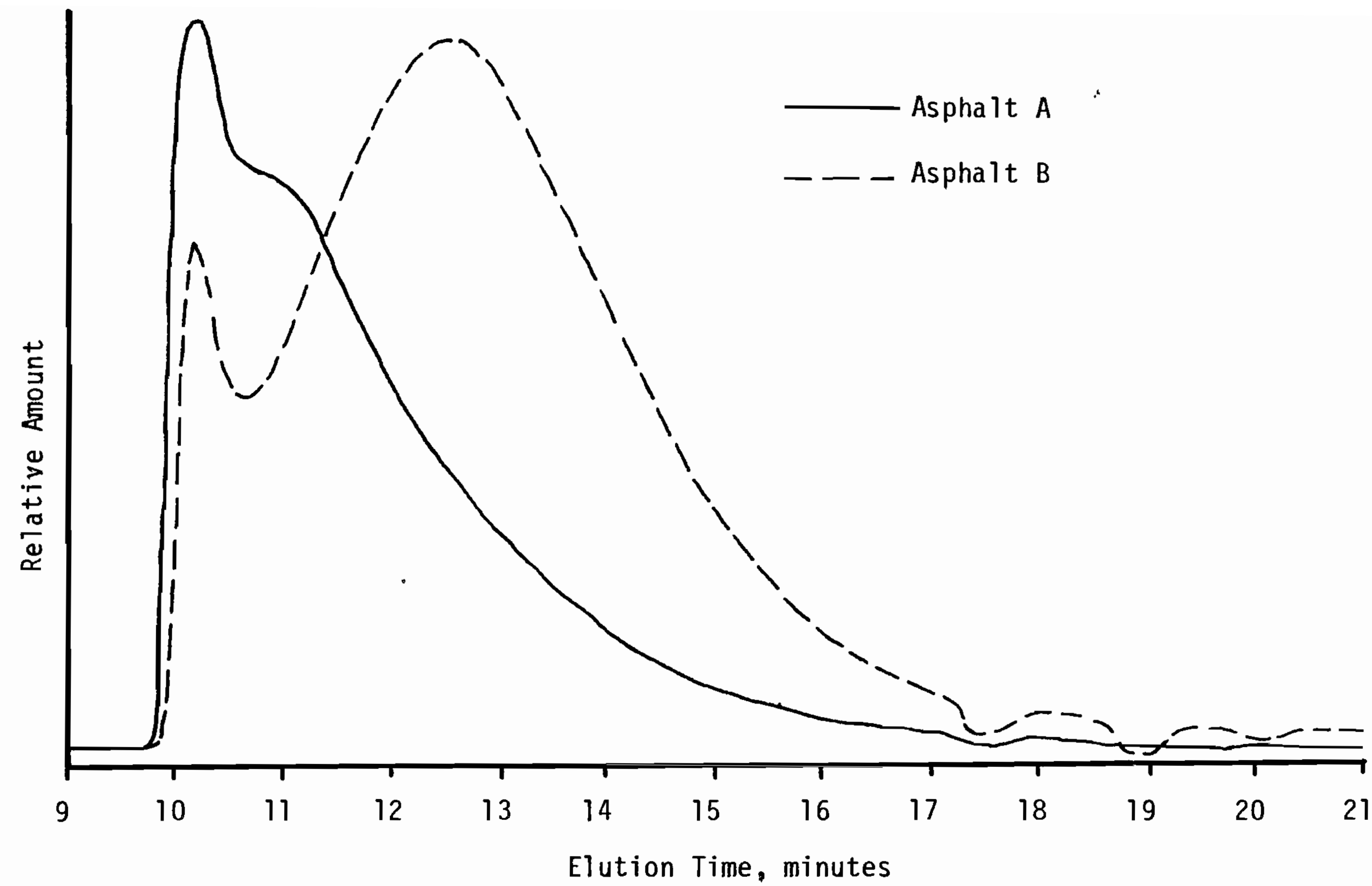

Figure 69. Chromatogram of Asphalts A and B, AC-20, Virgin Asphalt Cement Supplied by the Producer.

different at each location, the evaluation could only be performed within a given project. The physical mixture properties most likely to affect strength related to asphalt are shown for each location in Table 19. Note that, for the most part, asphalt content and air void content within a location are about the same. Figure 70 shows no relationship between stress at failure and asphalt type. Figures 71, 72, and 73 are chromatograms associated with the strength evaluation. These chromatograms are for the virgin asphalt cements delivered to the job site. All three figures are very similar as would be expected unless some change at the refinery took place.

Based on this limited information, there does not appear to be any correlation between the chromatograms and mixture strength. For this to be a predictive test, the GPC should be conducted on the original asphalt cement. However, chromatograms for the thin film oven test residue might be used and should be investigated.

Binder Aging Versus GPC

A possible use of the GPC is in the prediction of asphalt cement aging rate. The aging process hardens the binder, making it more brittle and less flexible. This will generally increase cracking potential due to fatigue and thermal activity.

Aging characteristics of three asphalts were evaluated from the Lufkin project. These asphalt cements were AC-20 grade. Asphalts C, D, and E were studied using the change in viscosity with time. In Figure 74, the viscosity at 140^{o}F for the virgin asphalt cement and asphalt cement extracted from cores one week old are compared. The differences exhibited by Asphalts C and D were those generally expected, while the difference seen in Asphalt E was excessive. Comparative chromatograms of each asphalt are shown in Figures 75, 76, 77, and 78. In all cases, there was an increase in the large size molecules. Due to a difference in scale, Asphalt E is shown in two figures while Asphalts C and E appeared to be very similar initially, but Asphalt E had a somewhat larger shift in molecular size. This shift was not as great as with

Table 19. Physical Mixture Test Results for Asphalt Strength Study.

Location	Grade	Producer	Asphalt Content, Percent	Air Void Content, Percent	Stress, 77 F, psi
Dickens	AC-20	A	4.9	5.5	177
		C	5.2	6.3	159
		E	5.2	6.7	140
Dumas	AC-10	A	6.2	5.5	63
		C	5.7	10.7	104
		E	5.8	6.1	126
Lufkin	AC-20	A	5.0	7.4	135
		C	6.7	4.2	266
		E	6.7	3.3	198

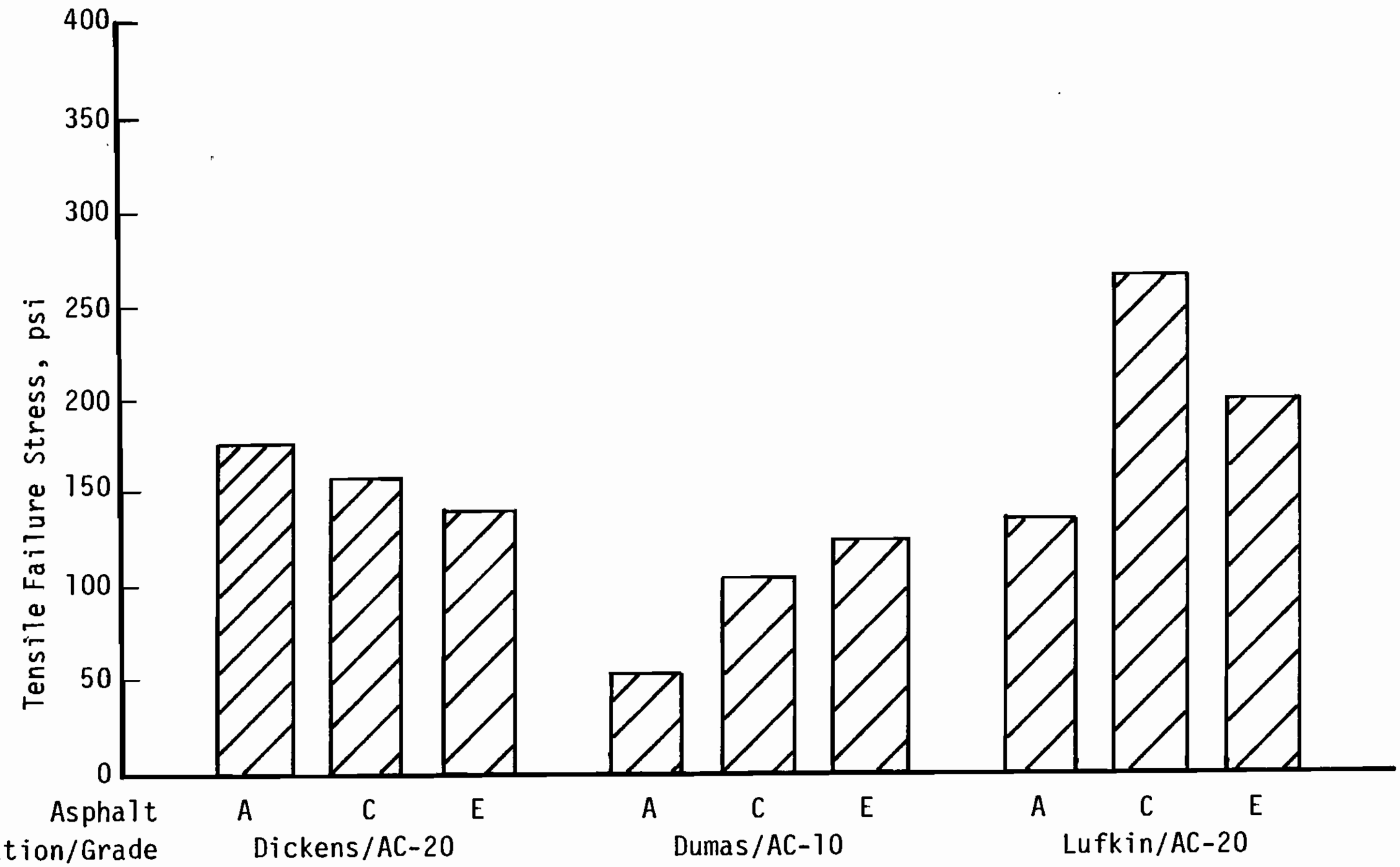

Figure 70. Asphalt Related to Tensile Strength by Location.

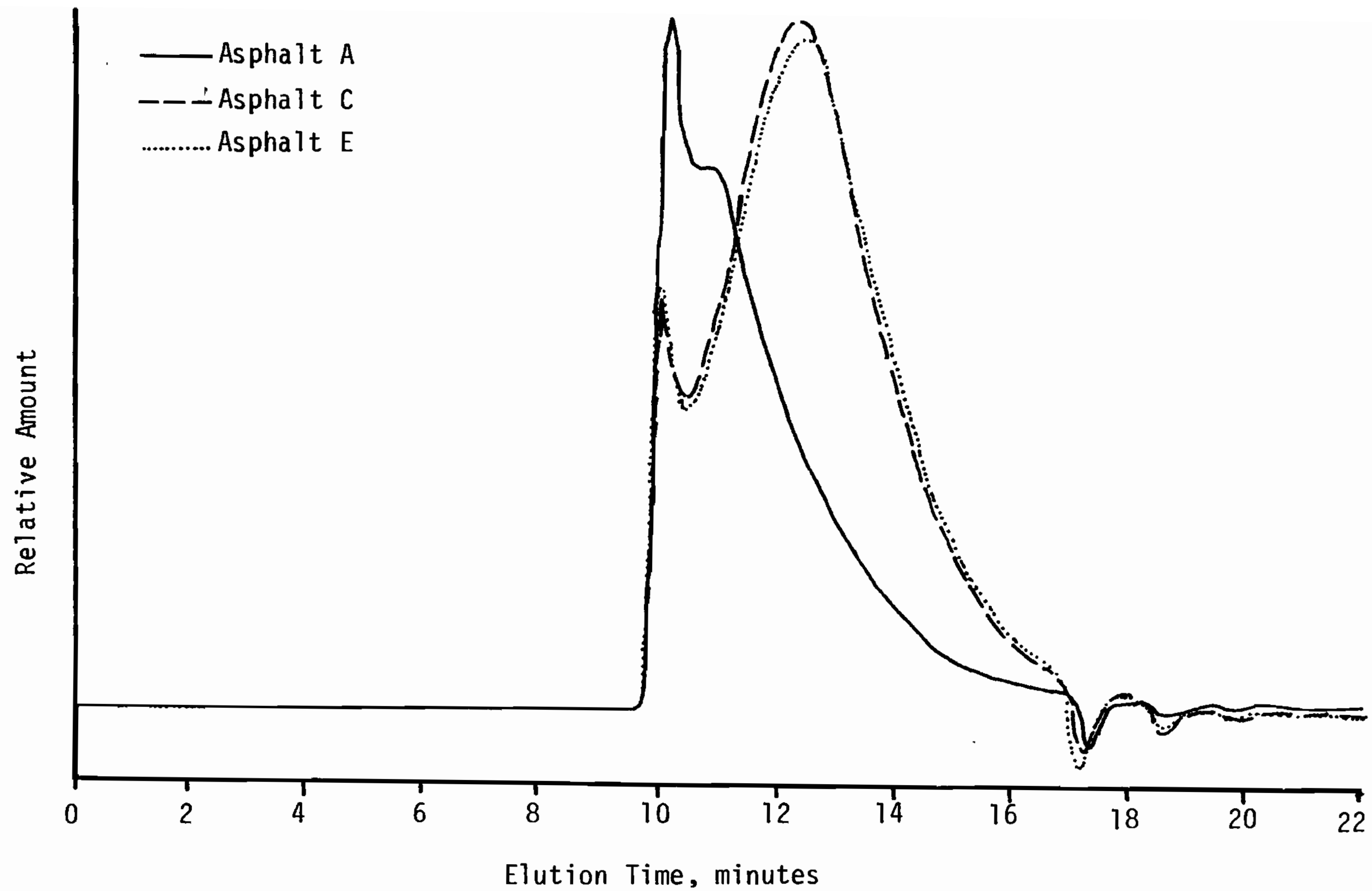

Figure 71. Relationship of Chromatograms of Three Virgin AC-20 Asphalt Cements from the Dickens Project.

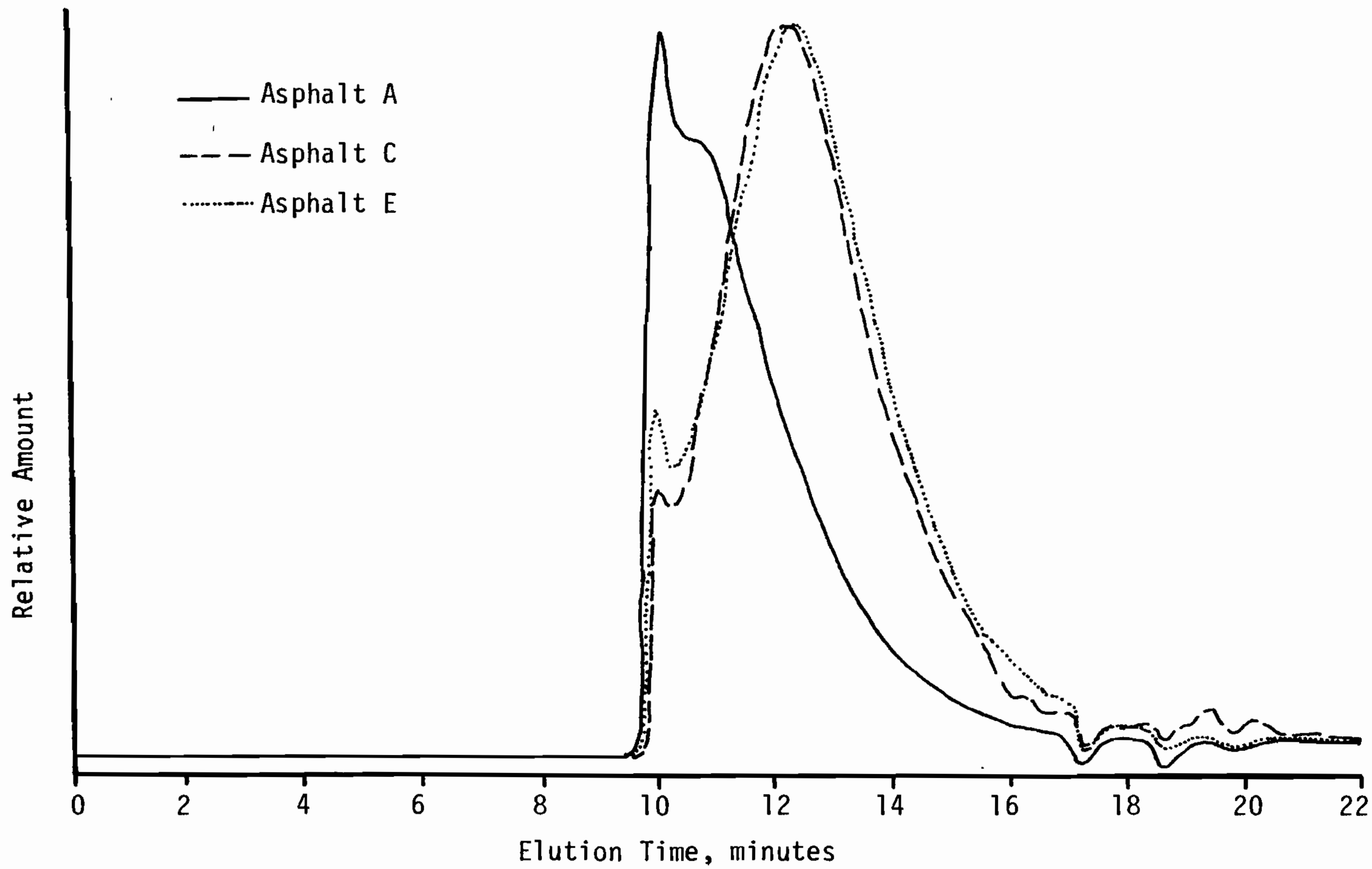

Figure 72. Relationship of Chromatograms of Three Virgin AC-10 Asphalt Cements from the Dumas Project.

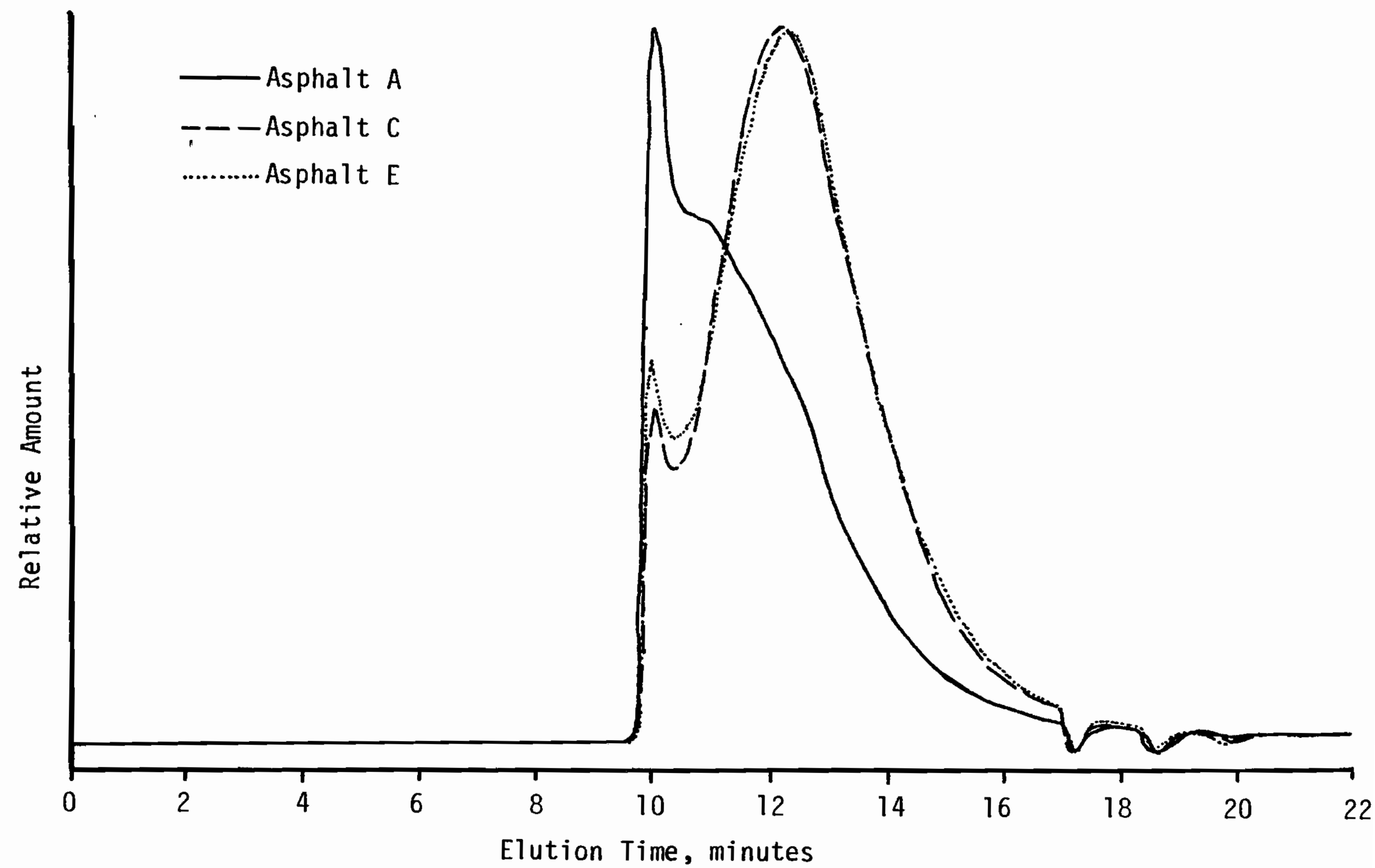

Figure 73. Relationship of Chromatograms of Three Virgin AC-20 Asphalt Cements from the Lufkin Project.

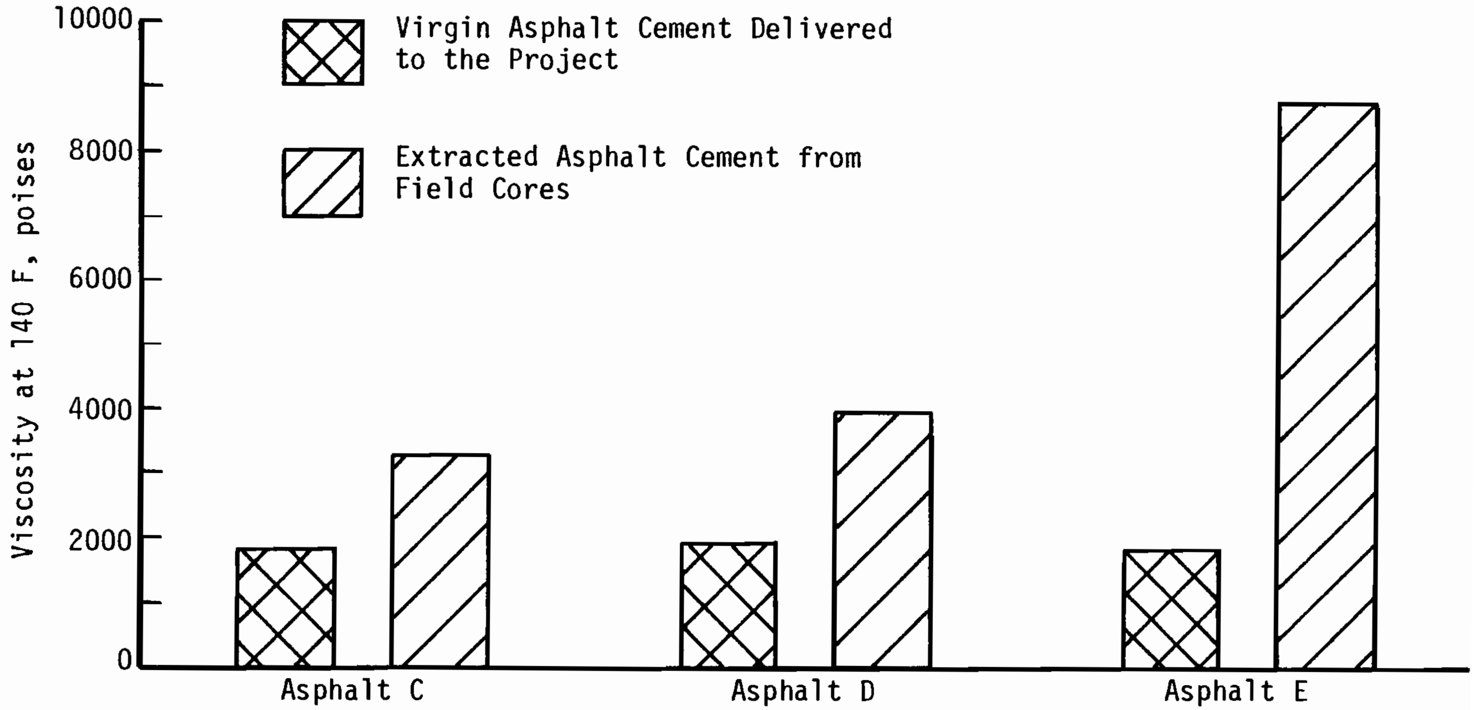

Figure 74. Change of Viscosity of Asphalts C, D, and E after One Week of Pavement Service from the Lufkin Project.

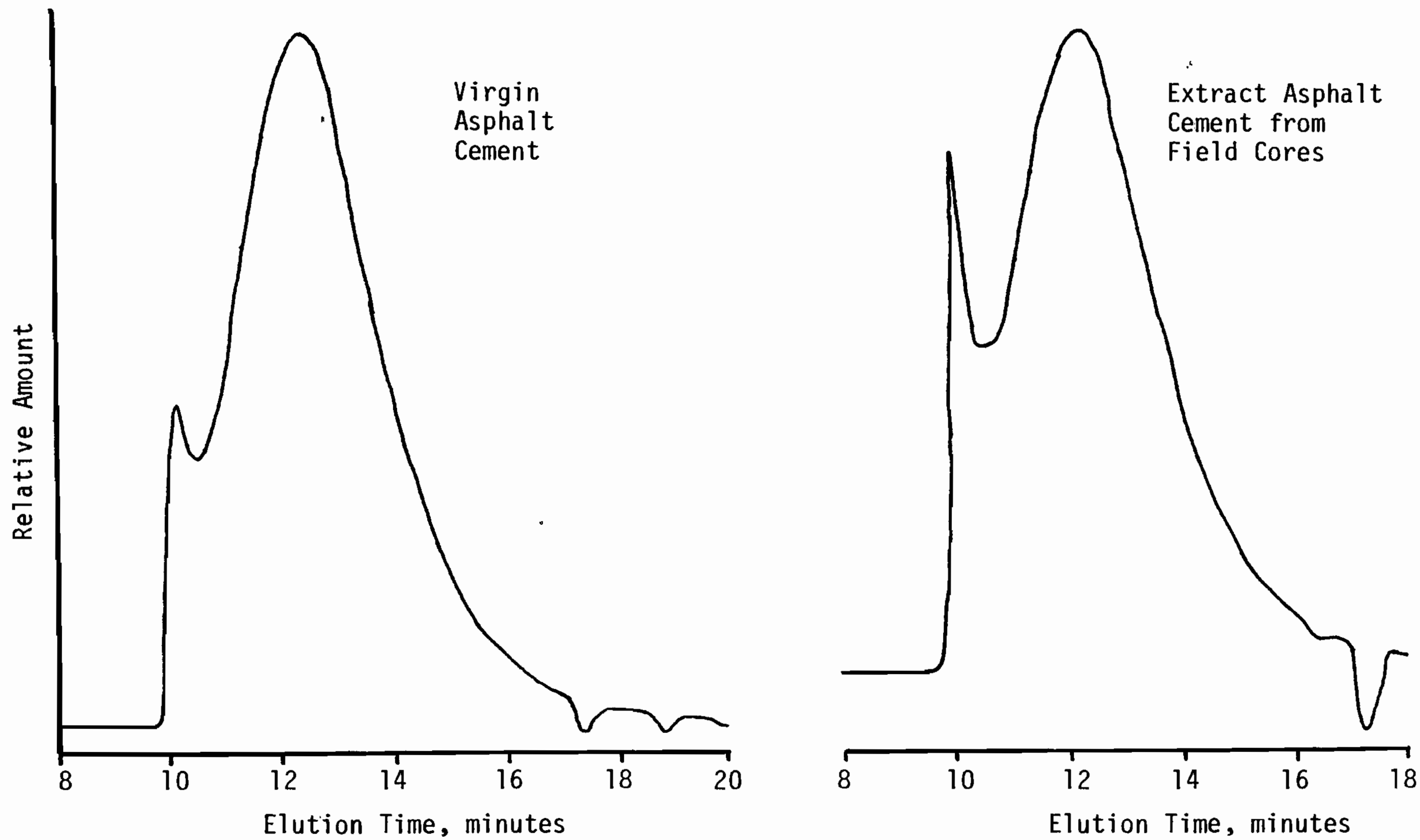

Figure 75. Comparison of Chromatograms of Asphalt C, AC-20 from the Lufkin Project.

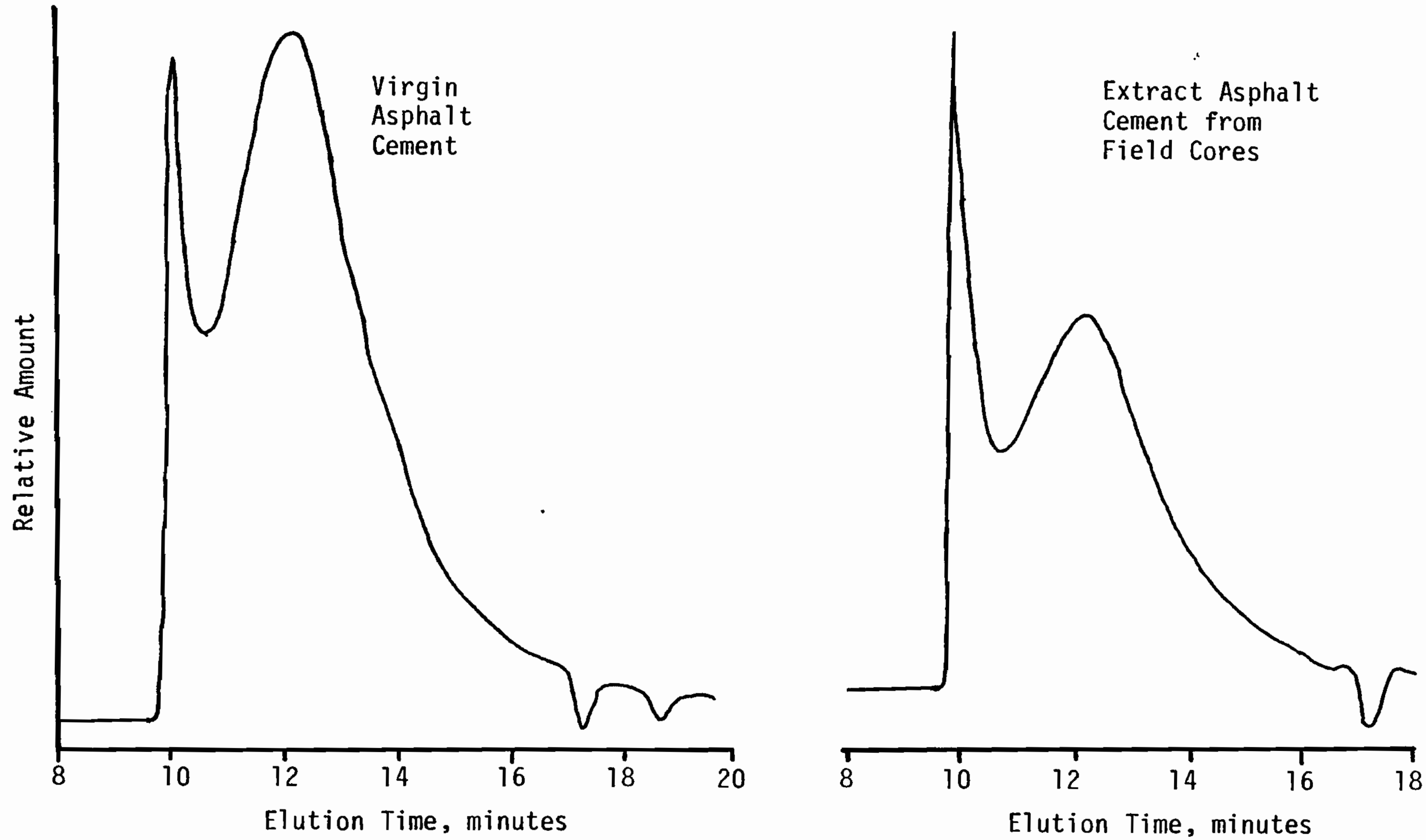

Figure 76. Comparison of Chromatograms of Asphalt D, AC-20 from the Lufkin Project.

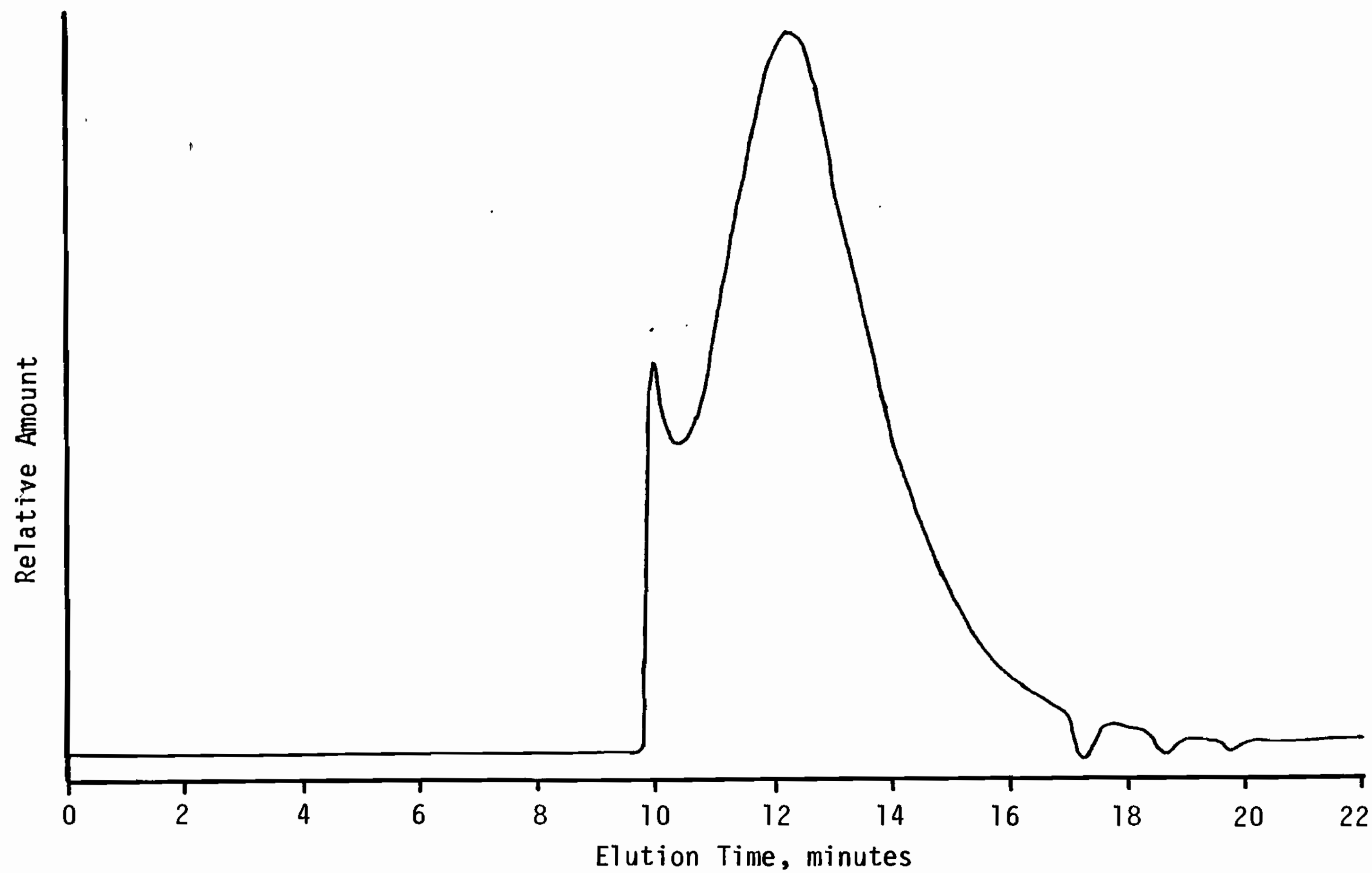

Figure 77. Chromatogram of Asphalt E, AC-20, Virgin Asphalt Cement from the Lufkin Project.

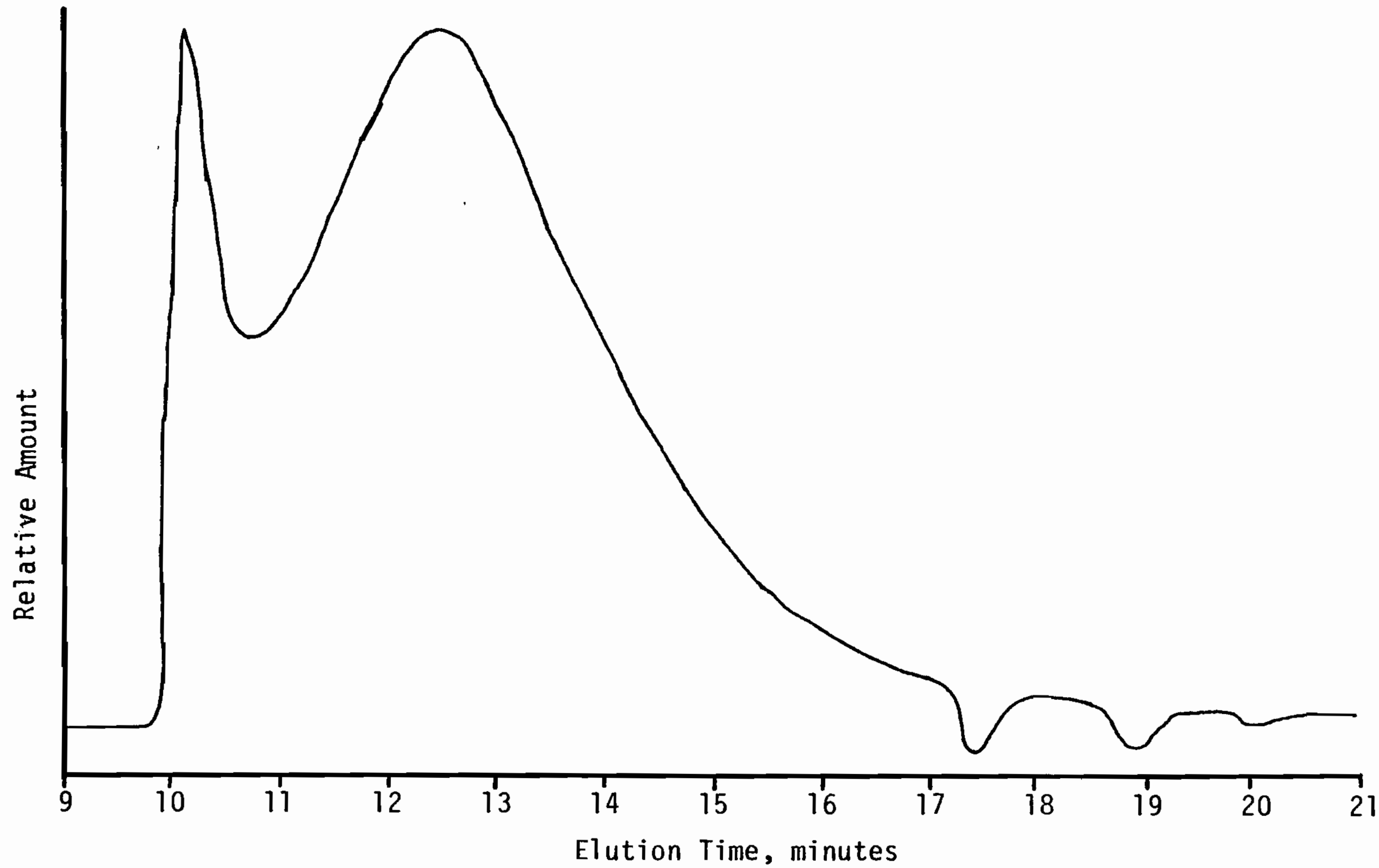

Figure 78. Chromatogram of Asphalt E, AC-20, Extracted from Lufkin Field Cores.

Asphalt D. Considering that Asphalt E showed the largest increase in viscosity and yet showed only a moderate change in the chromatogram when compared to the other two, it could be concluded that the GPC is not sensitive to viscosity changes brought about by aging.

Identification of Asphalt by GPC

Of the potential uses of the GPC in the asphalt industry, asphalt identification is thought to be the best and most immediate application. For the most part, the different asphalts can be recognized by their respective chromatograms. In Figure 79, three very different chromatograms for three different asphalt cements are shown. However, in Figure 80 Asphalt C and E produced remarkably similar chromatograms. As can be seen in Figure 80, Asphalt E had a little larger peak on the large molecule side than Asphalt C. This is also shown consistently in Appendix D. The viscosity-temperature relationship for the asphalts was also very similar, as shown in Figure 81 and no discriminating difference was found in the strength tests conducted. The aging tests, on the other hand showed a major difference between the two. This is one situation where GPC alone would not provide positive identification.

In relation to identification, it is possible to use the GPC to detect the presence of certain additives. Although this was not part of the original research, it was felt that this should be briefly presented. A virgin asphalt cement before the addition of an additive is shown in Figure 82. That same asphalt is shown in Figure 83 after an additive was introduced. Unfortunately, the elution time scales, are different so the chromatogram could not be overlayed. However, reference points at 10, 12, 13 and 17 minutes are provided to facilitate comparison. Note that there was a very definite shift toward larger molecular sizes afer the additive was introduced. This is one possible way of determining if an additive is present. Depending on how soluble the additive is in asphalt, the chromatogram will provide different information to indicate the presence of an additive.

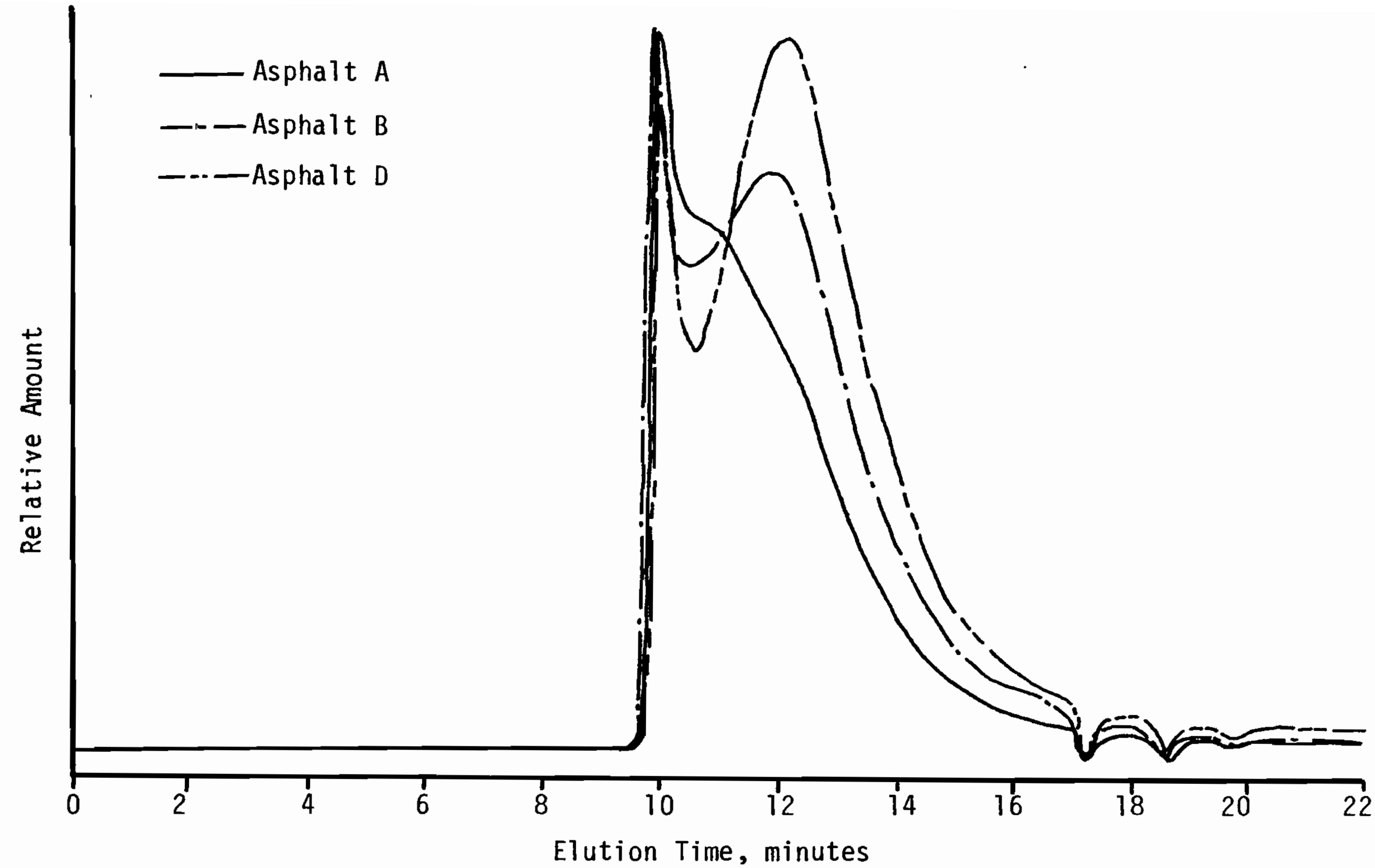

Figure 79. Chromatograms of Virgin Asphalts A, B, and D, AC-20 from the Lufkin Project.

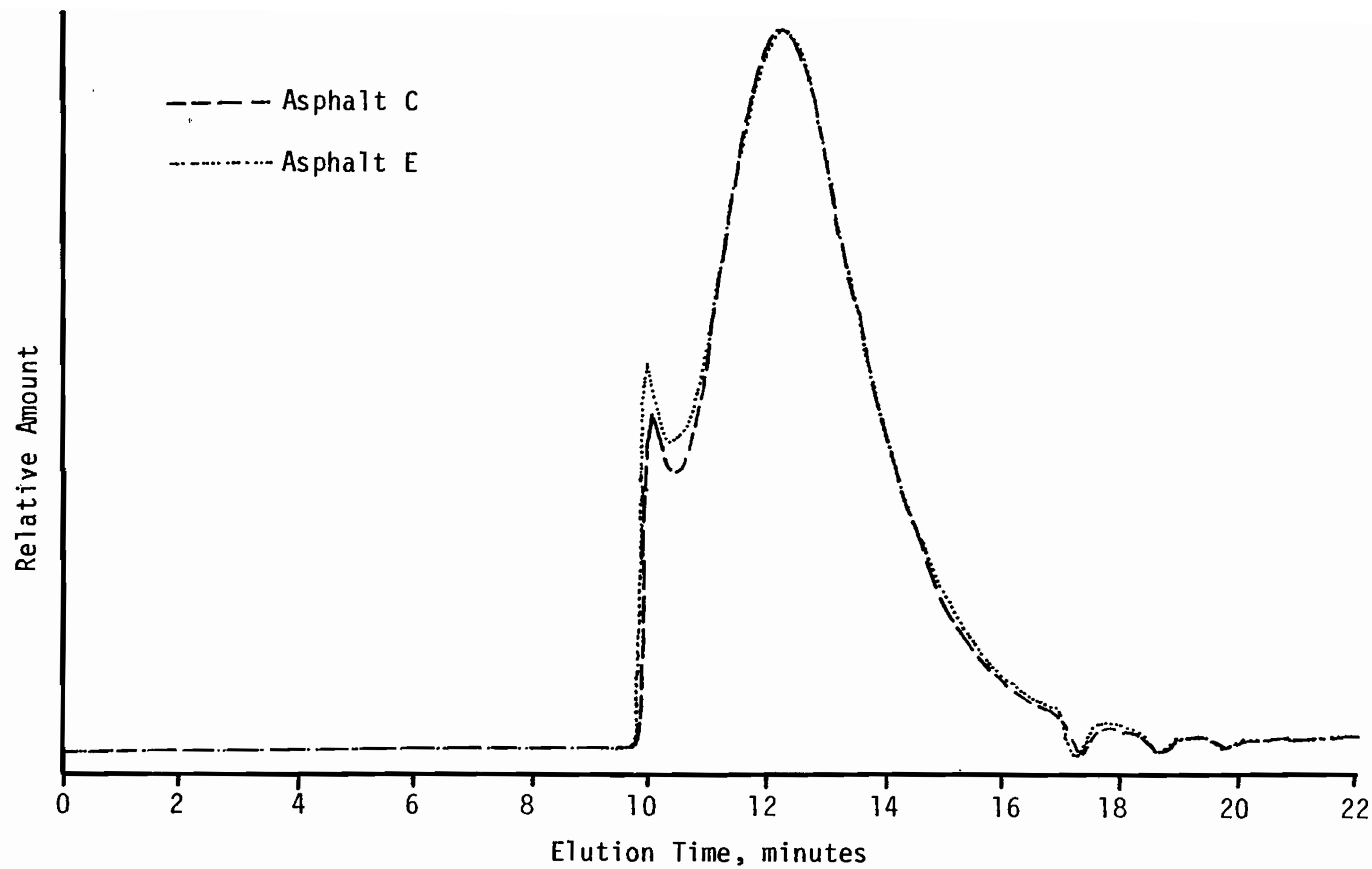

Figure 80. Chromatograms of Virgin Asphalts C and E, AC-20 from the Lufkin Project.

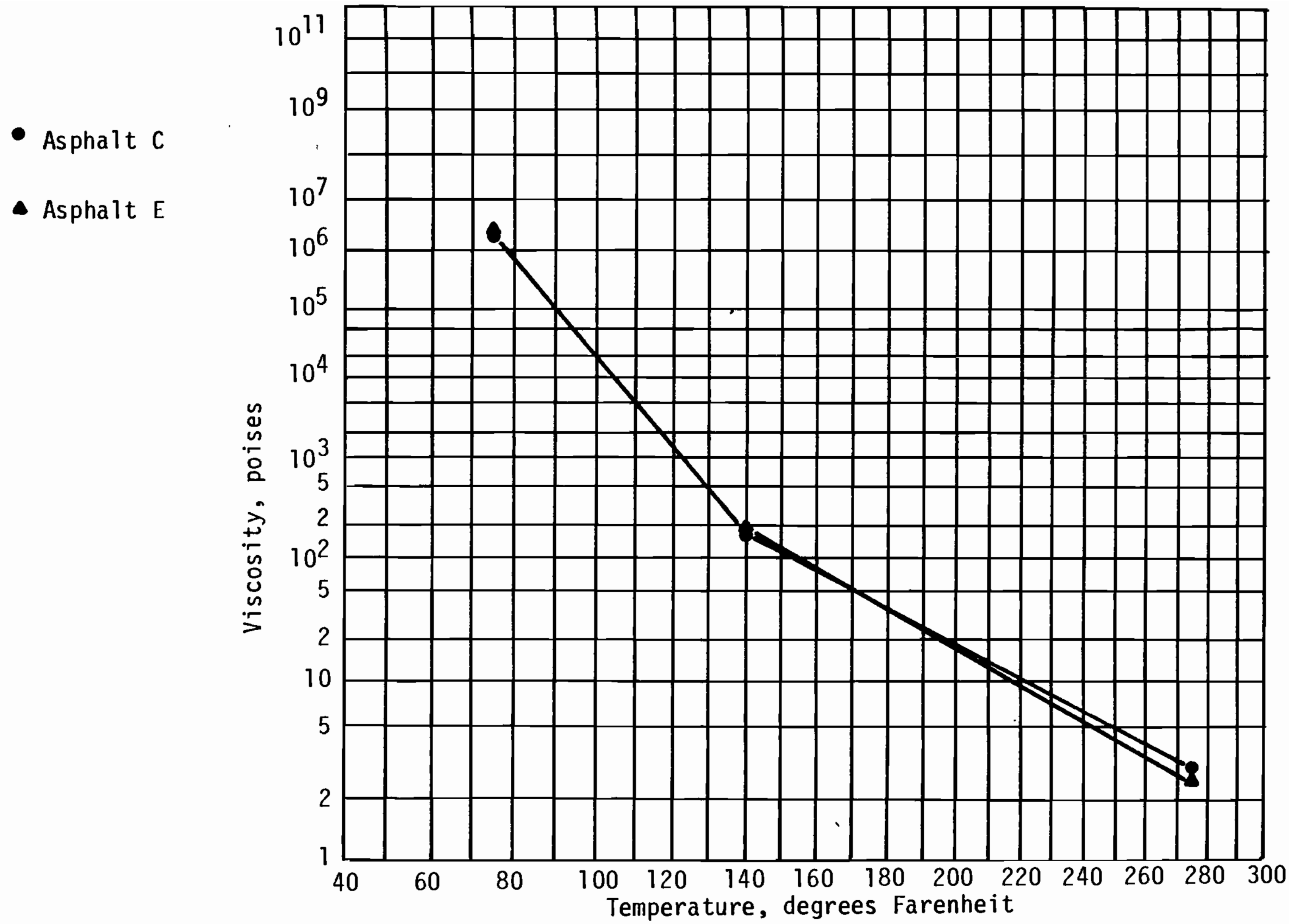

Figure 81. Temperature-Viscosity Relationship of Virgin Asphalt Cements C and E from the Lufkin Project.

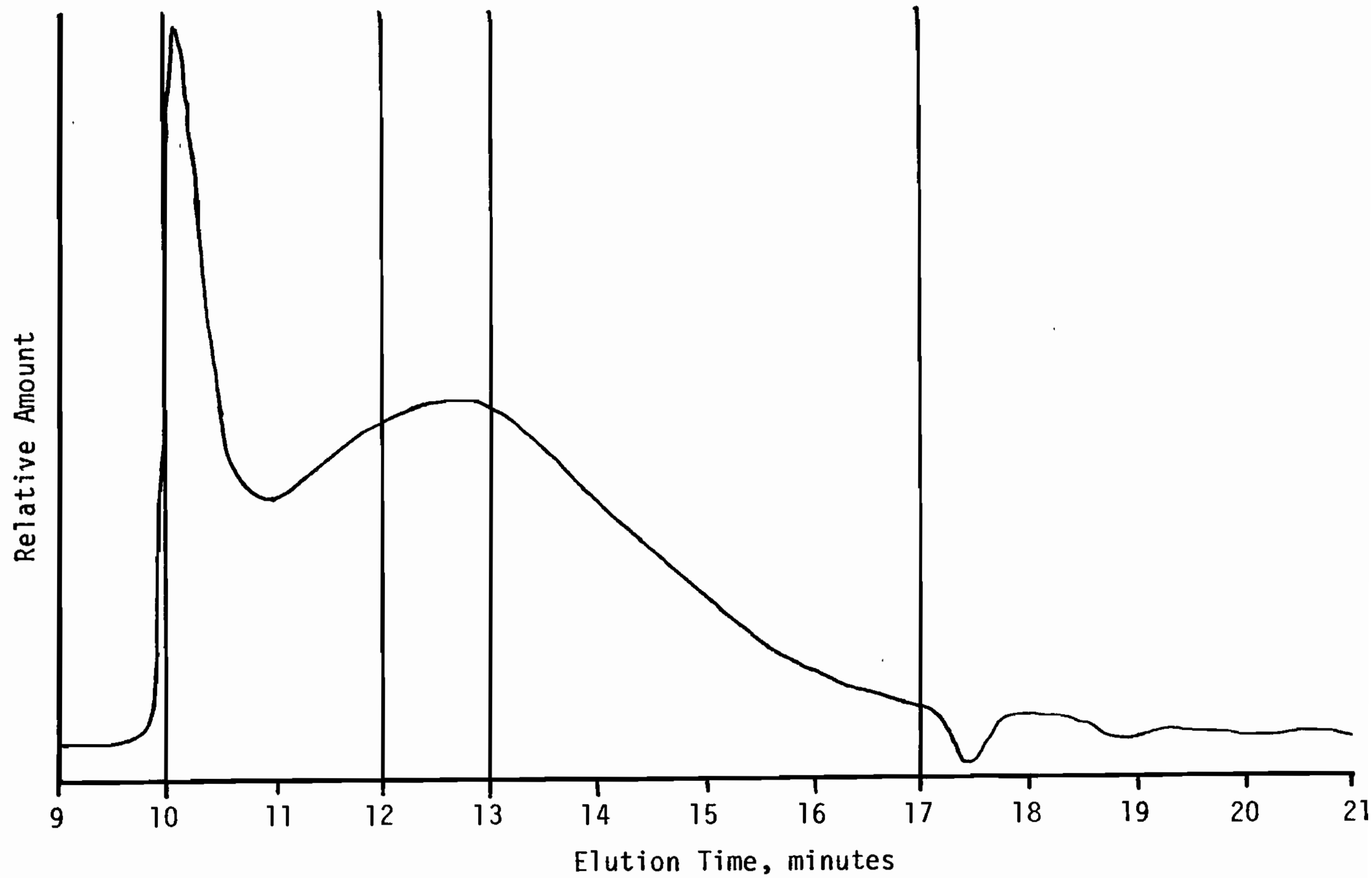

Figure 82. Chromatograms of a Virgin Asphalt Cement before Addition of an Additive.

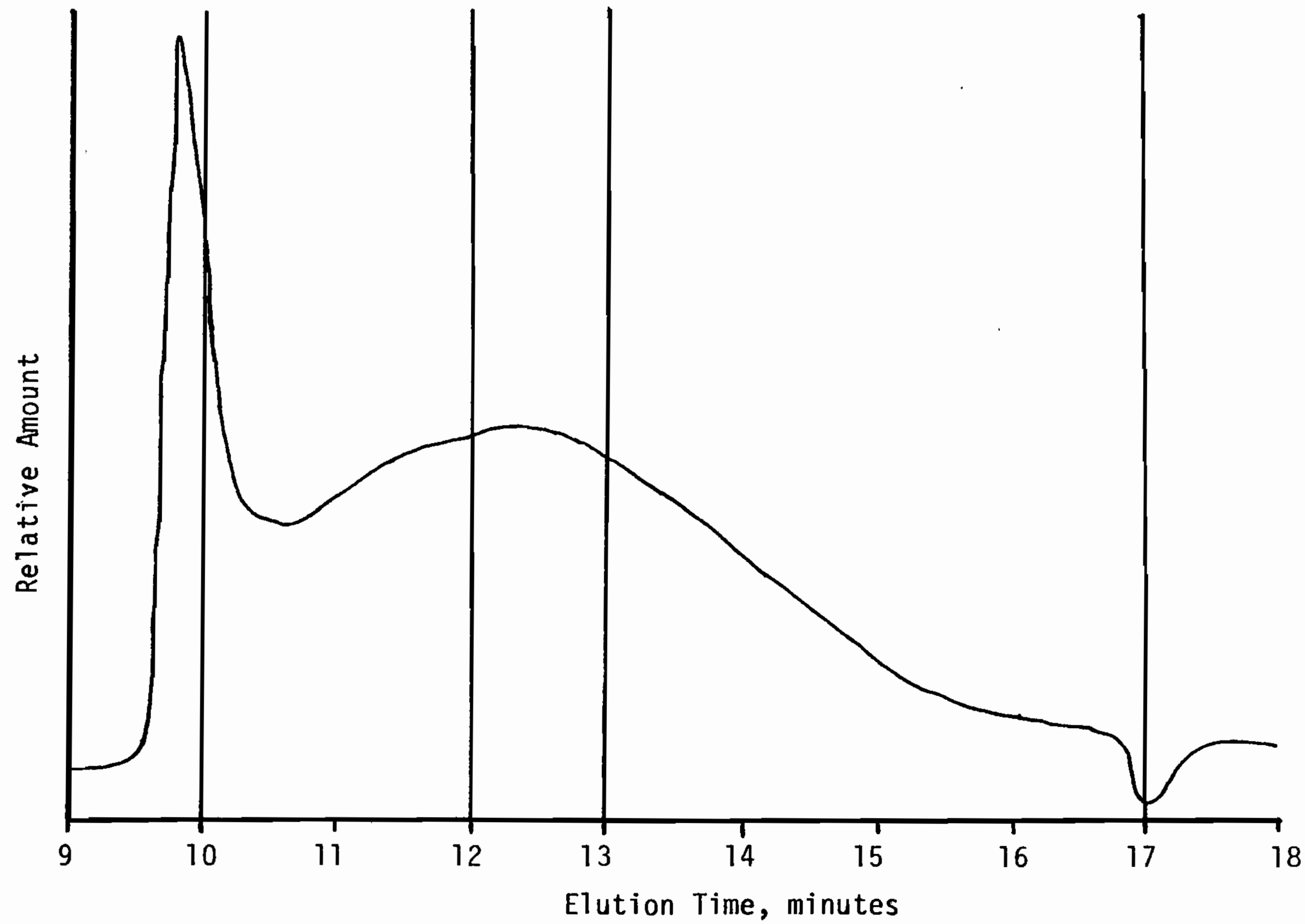

Figure 83. Chromatogram of a Virgin Asphalt Cement after Addition of an Additive.

It has been determined by other work that a change in refining technique or crude source will have an effect on the chromatograms produced by the GPC (59). With this in mind, a review of the data shows that the asphalts from each producer did not vary significantly between construction sites. Since GPC as well as the standard specification tests were performed on the virgin asphalt cements delivered to each of the sites in the study, it was possible to monitor the quality and consistency of the asphalts received. This proved to be of exceptional value at the Dumas project. As previously discussed, there was severe ravelling in the sections containing Asphalt B and C. These asphalts were foreign to that particular region having been shipped considerable distance specifically for this research project. Therefore, it is understandable when these sections failed and the others to performed well, that the binder would be suspect. A close investigation of these asphalts showed that Asphalt B from Dumas produced a somewhat different chromatogram than those delivered to the other locations. The chromatograms of Asphalt B showed an increase in the larger molecular sizes. Jennings's work would indicate an increase in cracking potential but physical properties on the extracted asphalt indicates the binder is remaining flexible.

Asphalt C was not different as defined by tests conducted and had the most severe distress. All the asphalts at each location met the standard Texas specifications for asphalt cements for their respective grade. Based on this information, one must conclude that the binder alone was not the problem and that other items should be more closely investigated, such as field compaction, aggregate absorption and asphalt content to name a few (52).

This is a good example of the use of GPC as a quality monitoring test. It was not used as a specification test, but did assure the user agency of the uniformity of the product received. By conducting GPC tests regularly and producing a library of chromatograms, a user agency could monitor the asphalt being used. At the same time, a data base would be generated from which further evaluation of the GPC test could be made.

GPC and Chemical Analysis

The GPC is a combination chemical and physical type test. Some say it is more physical than chemical since it is a form of molecular sieve analysis. Two chemical seperation procedures commonly used in the asphalt industry are the Rostler and Corbett analyses. The Rostler seperation is probably the more widely used of the two. In this procedure, the functional groups have been correlated with certain physical properties of the asphalt cement. The virgin asphalt cements supplied by the different producers were subjected to Rostler analysis. Results are shown in Table 4. In comparing the chromatograms with these results, it is well to note that Asphalt A has a low asphaltene content and yet has a high, large molecular size count as compared to Asphalt E which has a high asphaltene content. This means that the asphaltenes do not constitute the large molecular sizes. This presents the question of location of the different functional groups within the chromatogram. Work performed to date indicates that the functional groups are spread out across the full molecular size range (45).

Chapter VII

M_R AND DSE DETERMINATION

Testing Program - Leg A

In leg A of the testing program asphalt concrete specimens were aged at 140^{o}F. One would expect hardening and embrittlement of the asphalt following aging at this temperature. Prior to testing, the samples were placed in a 77^{o}F room to cool. All samples were tested at 77^{o}F.

Table 20 lists the results of these tests. Results are shown for the tests which occurred at 0, 3, 8, and 13 days into the aging process. The results confirmed that the asphalts hardened, as indicated by an increase in the M_R, and became more brittle, as indicated by DSE. These results indicate that chemical changes in the asphalt have produced a mixture with less potential to dissipate energy by viscosity response.

Table 21 lists the results of the Duncan multiple range analysis of the data. The purpose of the Duncan analysis is to indicate if the data acquired can be said to be different. This is accomplished by assigning the means to groups. Means which fall into a group cannot be said to be different than other means in that group. Means in a group, however, are statistically different from means in any other group. These test show that both the Schmidt device and the DSE procedure are capable of seperating the asphalt concrete mixtures by asphalt cements. As time of aging increased, however, the Duncan test showed fewer groupings or closer means. This would indicate that the hardening process eventually minimizes differences in the asphalts. Volitalization of some lighter weight components could be responsible for this occurrence.

Testing Program - Leg B

In leg B of the testing program samples were soaked in water at 140^{o}F. Table 22 lists the numerical results of the tests. Table 23 lists the statistical groupings of these data.

Table 20. Averaged Performance of Asphalt Samples Aged at 140°F in Leg A.

Age of Sample	Day 0		Day 3		Day 8		Day 13	
Asphalt	M_R (psi x 10^{-6})	DSE ($\frac{pi}{i^3}$ x 10^{-6})	M_R	DSE	M_R	DSE	M_R	DSE
E	.4368	188.54	.5107	122.0	.6081	49.43	.7569	47.86
A	.2137	395.48	.3988	190.9	.4820	110.56	.4700	116.95
C	.4977	175.69	.5093	167.9	.6311	98.27	.6990	81.89
D	.2820	340.43	.4189	175.3	.5005	117.96	.5663	82.95
B	.3388	239.41	.3483	216.5	.4515	151.6	.4794	98.3

Table 21. Duncan Groupings for Leg A. (Means with same letter are not significantly different Alpha level = 0.05.)

Day 0		Day 3		Day 8		Day 13	
Asphalt	Grouping	Asphalt	Grouping	Asphalt	Grouping	Asphalt	Grouping
Means from Resilient Modulus Determination							
C	A A	E	A A	C	A A	E	A A
E	A B B	C	A	E	A	C	A
A	C B C	B	B B	B	B B	B	B
B	C D D	D	B	D	B B	A	C C
D	D	A	C	A	B	D	C
Means from DSE Determination							
D	A A	A	A A	A	A A	D	A A
B	A	D	A B B	B	A B B	A	B A B A
A	B B	B	B B	D	B B	B	B A B A
E	B C C	C	B	C	B	C	B A B
C	C	E	C	E	C	E	B

Table 22. Averaged Performance of Asphalt Samples Aged at 140°F in Water in Leg B.

Age of Sample	Day 0		Day 3		Day 8		Day 13	
	M_R	DSE	M_R	DSE	M_R	DSE	M_R	DSE
E	0.4517	341.2	0.3728	153.3	0.3663	153.3	0.2798	334.1
D	0.2085	332.0	0.1806	341.2	0.1724	600.3	0.2103	460.8
C	0.3802	292.7	0.3590	292.7	0.3507	215.2	0.3460	272.4
B	0.2805	263.0	0.3498	332.0	0.3987	299.3	0.2213	418.9
A	0.3411	153.3	0.2707	263.0	0.2592	349.0	0.2131	404.9

Table 23. Duncan Groupings from Testing - Leg B. (Means with same letter are not significantly different Alpha = 0.05.)

Day 0			Day 3			Day 8			Day 13		
Asphalt	Group		Asphalt	Group		Asphalt	Group		Asphalt	Group	
Means from Resilient Modulus Determination											
E	A		E	A		E	A		C		A
	A			A			A				A
C	A	B	C	A	B	C	A		E	B	A
		B		A	B		A			B	
A	C	B	B	A	B	B	A	B	B	B	
	C				B			B		B	
B	C	D	A		B	A		B	A	B	
		D								B	
D		D	D	C		D	C		D	B	
Means from DSE Determination											
D	A		D	A		D		A	D	A	
	A			A						A	
B	A		B	A		A	B		B	A	B
	A			A			B			A	B
C	A		C	A		B	B	C	A	A	B
	A			A			B	C		A	B
A	A	B	A	A	B	C	B	C	E	A	B
		B			B			C			B
E		B	E		B	E		C	C		B

The DSE of the samples increased with time in the program, while the M_R decreased. At all times, however, the tests were able to divide the results into seperate groupings.

The softening of the asphalts with time in hot water is to be expected. Several theories have been suggested to explain this phenomena. Included are the displacement concept (70), the detachment concept (71), the chemical disbonding concept (72), blistering and pitting concept (73), and the pore pressure concept (74). Of these concepts, only the pore pressure concept would not apply to the test conducted. This hypothesis relies on the presence of dry heat to aid in its conclusion. In disregard of the particular concept, or group of concepts which might apply specifically to the mechanical breakdown of the mix, the asphalt suffers a loss of cohesiveness and adhesiveness which results in softening.

Correlations With Cement Properties

The primary purpose of supplying data from the asphalt cements was to substantiate and illuminate the differences and similarities of the cements. Some linear regressions were performed, however, and are included for completeness.

DSE as measured in leg A should indicate the embrittlement of the asphalt with age and heat. Several other parameters would logically relate to this embrittlement. Table 24 illustrates the linear correlation coefficients obtained from comparing DSE in leg A at day 13 with some of the determined asphalt cement properties.

With few exceptions, significant relationships were not found. Those relationships found valid are Rostler analysis components and the Rostler parameter.

The relationships shown would seem logical when examined independently. The Rostler parameter was designed to indicate asphalt stability and would appear to do so. The relationship with the individual components would appear rational when examined also.

Asphalts with a high asphaltene content, for example, would resist chemical activity better than those with a lower asphaltene content but with more of the reactive components.

Table 24. Linear Correlation Coefficients from Leg A.

	Correlation Coefficients for Leg A DSE at 13 Days
Corbett Analysis	
Asphaltenes	0.08
Saturates	-0.31
Non-Polar Aromatics	0.18
Polar Aromatics	-0.01
Rostler Analysis	
Asphaltenes	0.83
Nitrogen Bases	-0.14
First Acidaffins	-0.84
Second Acidaffins	0.71
Paraffins	-0.13
Rostler Parameter	0.71
Thin Film Oven Test	
Δ Penetration	-0.08
Δ Viscosity	-0.55
Rolling Thin Film Oven Test	
Δ Penetration	0.31
Δ Viscosity	0.38

Multiple linear regressions were performed using DSE, as measured in leg A, as the dependent variables, and the Corbett and Rostler fractions as independent variables. The results of this analysis are indicated in Table 25.

Table 25. Multiple Linear Regressions Between DSE in Leg A and Chemical Fractions.

Corbett Analysis

Dependent Variable DSE in Leg A

Independent Variable	Regression Coefficient
Asphaltenes	119.12
Saturates	116.02
Non-Polar Aromatics	98.26
Polar Aromatics	96.51

Constant: -11809.46

Standard Error of Estimate: 29.29

R Squared: 0.475

Multiple R: 0.689

Rostler Analysis

Dependent Variable DSE in Leg A

Independent Variable	Regression Coefficient
Asphaltenes	-11.64
Nitrogen Bases	-11.50
First Acidaffins	-24.37
Second Acidaffins	-27.71
Paraffins	0

Constant: 1619.47

Standard Error of Estimate: 14.20

R Squared: 0.835

Multiple R: 0.914

Chapter VIII

Blunt Nose Penetrometer Test Results

Another study by TTI (41) used the blunt-nosed penetrometer on the test section near Dickens. Examples of test results are shown in Tables 26, 27, 28. Table 26 shows extreme variation in data collected at several temperatures using penetrometers of three diameters. This is typical of much of the data collected. Somewhat more uniform results were obtained using the 1/4-inch diameter penetrometer with an applied load of 8 pounds (Tables 27 and 28). The penetrometer seems to be sensitive to asphalt viscosity as evidenced by the difference in penetration when comparing AC-10 and AC-20 under similar conditions (Figure 84). Figure 85 shows that the correlation between the penetrometer test and oven aged asphalt viscosity at 140°F is not good.

The blunt-nose penetrometer is capable of measuring relative differences in mass viscosity of conventional hot mixed asphalt concrete above 100°F. However, variability of the data within a series of tests on a single material at a given temperature is considered intolerable by the authors. It is believed that the primary cause of this variation is that the diameter of the larger aggregate is as large as or larger than the diameter of the blunt-nose of the penetrometer. Measurements largely depend upon the proximity of these coarse aggregate particles to the tip of the penetrometer.

Tests using the 1/4-inch diameter penetrometer and a mix temperature near 140°F seems to give the most uniform results. If a large number of tests (say 20 or more) were performed and statistical methods were utilized to elimate outliers, it is believed this test may be of practical value as a field test.

Table 26. Blunt-Nose Penetration Data from Field Test Pavements near Dickens, Texas.

Asphalt Refinery	Nose Diameter, inches	Weight Applied, pounds	Temp °F	Compactive Effort at Time of Test	Times required for 1/4-inch penetration, sec
B AC-20	1/4	16	140	One pass Vibratory roller + One pass Steelwheel roller	8 7 120+ 120+ 15 11
	1/2	20	160	One pass Vibratory roller + One pass Steelwheel roller	11 20 10 43 92
	3/4	4.3	215	None	4 4 4 2 1
C AC-20	1/4	16	140	One pass Vibratory roller	240+ 12 8 2 21
	1/4	16	132	One pass Vibratory roller + One pass Steelwheel roller	102 49 9 6 8
	1/4	16	110	Completed 1 pass vibratory + 2 pass steelwheel + pneumatic	98 180+ 180+

Table 27. Blunt-Nose Penetration Data at 140°F from Field Test Pavements near Dickens, Texas*.

Asphalt Producer	Asphalt Grade	Time required for 1/4-inch penetration, sec	Average Time, sec
E	AC-10	3 6 3 5 5	4
	AC-20	14 15 15 90	34
D	AC-20	18 4 9 5 5 15	8
A	AC-10	<1 3 2 3	3
	AC-20	15 14 45 40	29

*All tests were performed at 140°F using the 1/4-inch diameter penetrometer with a load of 8 pounds after one pass of vibratory roller and 2 passes of steelwheel roller.

Table 28. Blunt-Nose Penetrometer Data at 160°F from Field Test Pavements near Dickens, Texas*.

Asphalt Producer	Asphalt Grade	Time Required for 1/4-inch penetration, sec	Average Time, sec
E	AC-10	7 8 4 3 5	5
	AC-20	13 12 8	11
D	AC-20	2 8 8 2 2	4
A	AC-10	<1 3 2 1	2
	AC-20	15 14 40 10	20

*All tests were performed at 160°F using the 1/4-inch diameter penetrometer with a load of 8 pounds and after one pass of vibratory roller and 2 passes of steelwheel roller.

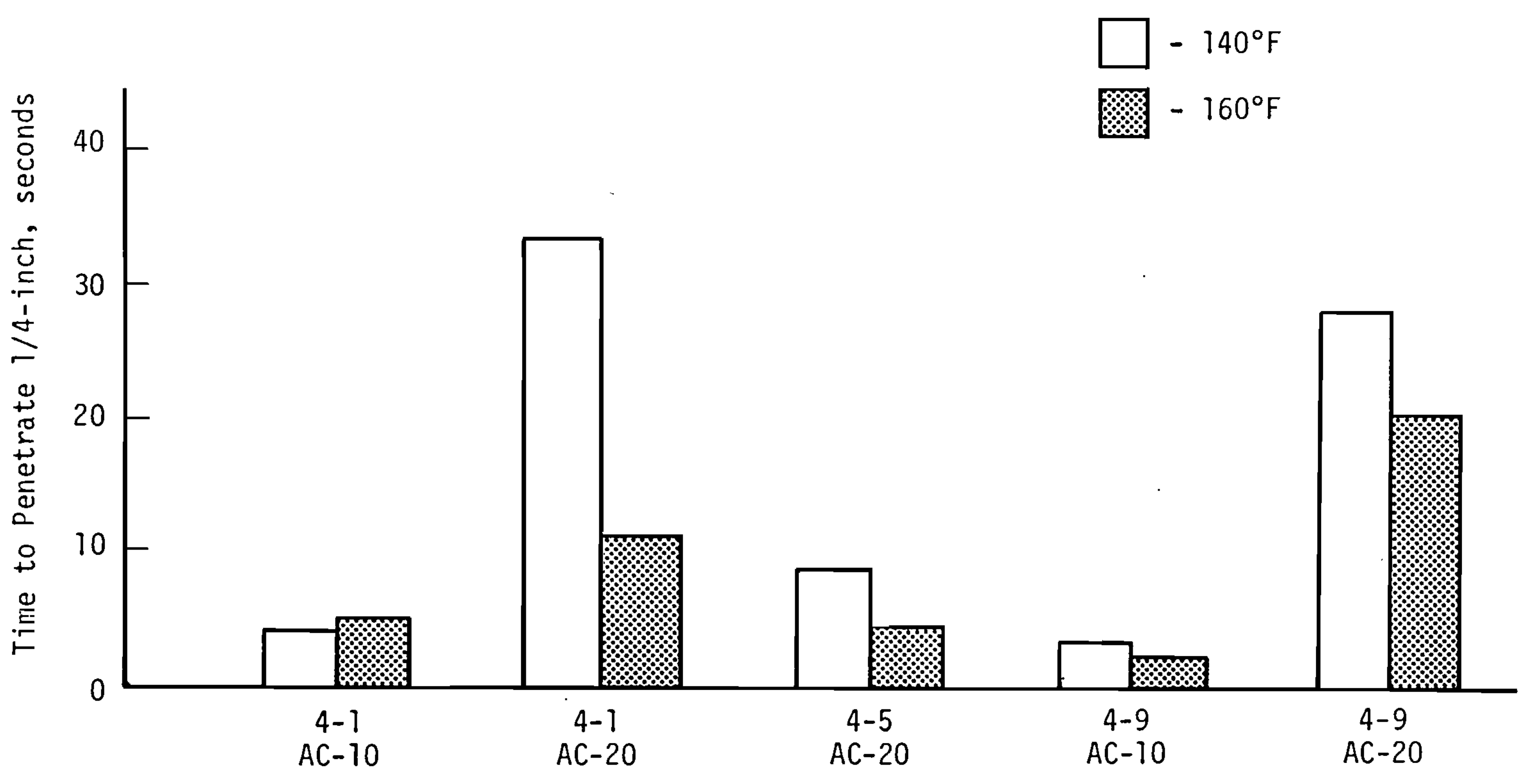

Figure 84. Blunt-Nose Penetrometer Data as a function of Asphalt Source and Grade.

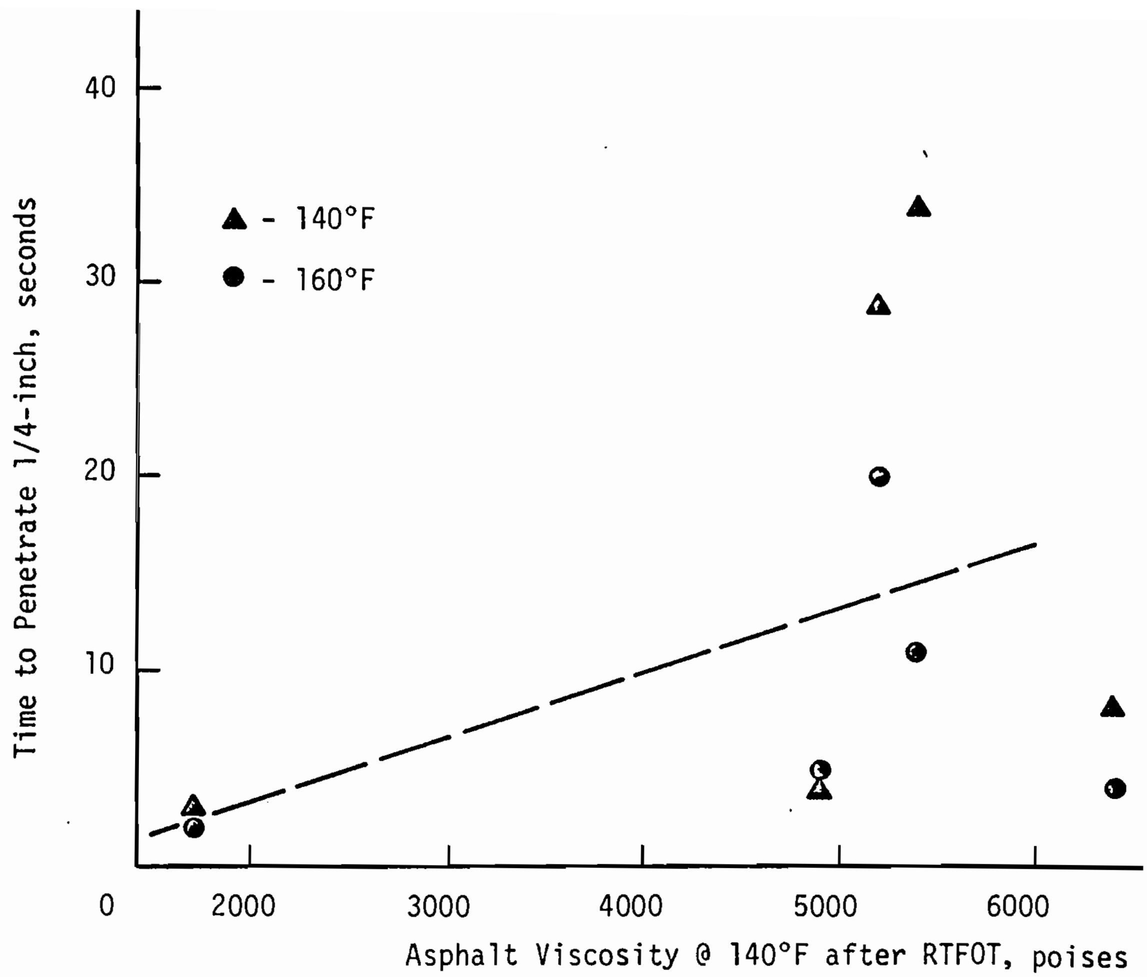

Figure 85. Blunt-Nose Penetrometer data versus Asphalt Viscosity.

Chapter IX

FIELD PERFORMANCE EVALUATION RESULTS

Performance evaluations were performed at two different times for all test pavements within each location. The first was immediately following construction to identify any visible problems or distress and to establish a reference. The second evaluation took place approximately one year thereafter.

Dickens, Texas Location

Initially the pavement appeared satisfactory with no visible signs of distress. It did, however, appear to be more coarse than most Texas Type D asphaltic hot mixtures previously observed. After one year's service, there was still no major distress, but the surface appeared dry and coarse. This might be an early indication of impending raveling although that was not evident at the time. The highway department personnel in charge of maintenance decided that a fog seal was in order and proceeded in the following year to seal the surface. The sections all appeared virtually the same with no one asphalt performing any different from the other based on the visual evaluations.

Dumas, Texas Location

Immediately following construction the pavement appeared to be in excellent condition. There were no visible problems and the construction apparently proceeded well. However, within two months the sections with Asphalts B and C began to ravel severely. For this reason, those pavements were evaluated after two months. Raveling in some cases was down to the original pavement surface in these two sections. The section with Asphalt C was clearly the most distressed but the Asphalt B section was also in poor condition. The other sections showed no visible signs of distress. By the end of the first year, the section with Asphalt C had to be removed and replaced. The section with Asphalt B was partially removed and replaced leaving a portion intact that had not raveled severely enough to have to be removed at that time. The other sections appear to be doing fine without any signs of distress after one year's service.

Lufkin, Texas Location

The Lufkin location was constructed one year after the Dumas project. Initially, the surface appeared to have more asphalt or a denser gradation than the previous two projects. The gradation curves in Chapter II and the asphalt cement contents reported in Appendix C indicate that this mix is out of specifications on the percent retained on the Number 10 sieve. It was specified as a Texas Type D asphaltic hot mixture as were the other two locations. There were no visible signs of distress and the overall appearance was very good. The pavement has shown no signs of distress and is continuing to perform well.

Chapter X

Conclusions and Recommendations

Conclusions

1. The test pavements in Lufkin are all performing well with no signs of distress.
2. The test pavements in Dickens began to show signs of raveling before a fog seal was placed over them in 1985. To date, all sections are performing equally well.
3. The test section in Dumas containing Asphalt C had to be removed and replaced after one year of service. The cores taken at one year on this section had air voids as high as 15.4%. A portion of the section containing Asphalt B also had to be removed and replaced. Based on the laboratory tests and the field performance of the Dickens and Lufkin test sections, there is no indication that the asphalt was the primary cause of the failure.
4. The excessive air void contents in Dumas and Dickens caused the mixtures to exhibit low values of stability, strength and stiffness.
5. Based on the field performance data to date, the different asphalts in this study are exhibited equivalent performance.
6. When reasonably good quality angular aggregate with proper grading is employed to produce asphalt concrete, relatively soft asphalts and/or asphalts that have not been hardened as predicted by oven tests can be utilized without adversely affecting mixture toughness or workability.
7. The resilient modulus and indirect tensile tests at 77^{o}F are much more sensitive to asphalt consistency than either the Hveem or Marshall stability tests.
8. Asphalt temperature susceptibility can adversely affect compaction of hot mixed asphalt concrete.

9. Gel Permeation Chromatography will produce chromatograms that will allow identification of different asphalt cements.
10. There is no apparent correlation between the chromatogram shape and stress at failure as determined by the indirect tension test.
11. There is no direct correlation between the asphalt chromatogram shape and aging as observed by change in viscosity, but the shape does show change with age.
12. Gel Permeation Chromatography will produce similar chromatograms for asphalt grade AC-10 and AC-20 from the same producer.
13. The GPC will indicate the presence of an additive or some other foreign material in the asphalt cement in a comparative analysis of the chromatogram of the virgin asphalt cement.
14. The GPC provides a means for monitoring the continuing consistency of asphalts.
15. The testing program indicated that the measure of dissipated strain energy (DSE) was sensitive enough to differentiate between the reactions of different asphalts to the testing procedures.
16. Because the DSE tests were able to differentiate between asphalts, it has potential as an aid the engineer in selecting asphalts or asphalt additives which would retard the hardening of asphalts. This would be beneficial in analyzing the comparative resistance of the materials to crack propagation.
17. Careful analysis of the data in leg B reveals a problem in using DSE as a parameter of asphalt quality. The materials response to the hot water soaking was a general softening or weakening of the asphalt. This weakening was subtantiated by the reduction in M_R (Modulus of Resiliency). The DSE of the samples increased during this process. This result is expected. DSE depends upon the amount of energy placed into the sample.
18. The blunt-nosed penetrometer is unacceptable for the purpose of measuring mixture toughness of in-place asphalt concrete paving mixtures.

Recommendations

1. Continue monitoring the test roads to evaluate long term field performance, and determine correlations with present and future laboratory data.
2. The use of the GPC as an identity test appears to be acceptable. However, no correlation to pavement performance established by this preliminary research. In order to improve the probability of developing correlations between GPC and performance, the following recommendations are suggested:
   A) Perform GPC on the different Rostler fractions to determine the molecular size range of each.
   B) Divide the chromatograms into several molecular sizes and determine the fractions present in each.
   C) Compare chromatograms of asphalts that are water susceptible with those that are not.
   D) Perform more GPC tests on asphalts with additives to establish the effect of each on the chromatograms.
3. The goal of the DSE portion of the study was to measure the applicability of the test, which has been satisfied. By careful analysis and study, quantifications of the data shown should be possible. Study of these properties and analysis of work done in the area of fracture mechanics might lend an invaluable step towards predicting pavement distress.

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APPENDIX A

Standard Asphalt Cement Specifications of the Texas State Department of Highways and Public Transportation

Table A1. Texas State Department of Highways and Public Transportation Specifications for Viscosity Grade Asphalt Cements.

Properties	AC-1.5 Min.	AC-1.5 Max.	AC-3 Min.	AC-3 Max.	AC-5 Min.	AC-5 Max.
Viscosity, 140 °F, Stokes	150±50		300±100		500±100	
Viscosity, 275° F, Stokes	0.7	-	1.1	-	1.4	-
Penetration, 77° F, dmm	250	-	210	-	135	-
Flash Point, ° F Cleveland Open Cup	425	-	425	-	425	-
Solubility in Trichloroethylene, Percent	99.0	-	99.0	-	99.0	-
Tests on Thin Film Oven Residues						
Viscosity, 140 F, Stokes	-	450	-	900	-	1500
Ductility, 77 F, cm	100	-	100	-	100	-
Spot Test	NEGATIVE FOR ALL GRADES					

Table A1. Continued.

Properties	AC-10 Min.	AC-10 Max.	AC-20 Min.	AC-20 Max.	AC-40 Min.	AC-40 Max.
Viscosity, 140°F, Stokes	1000±400		2000±400		4000±800	
Viscosity, 275°F, Stokes	1.9	-	2.5	-	3.5	-
Penetration, 77°F, dmm	85	-	55	-	35	-
Flash Point, °F Cleveland Open Cup	450	-	450	-	450	-
Solubility in Tricholorethylene, Percent	99.0	-	99.0	-	99.0	-
Tests on Thin Film Oven Residues						
Viscosity, 140°F, Stokes	-	3000	-	6000	-	12000
Ductility, 77°F, cm	70	-	50	-	30	-
Spot Test	NEGATIVE FOR ALL GRADES					

APPENDIX B

Results of the Standard Physical Tests

Table B1. Physical Properties of the Experimental AC-20 Grade Asphalt Cements.

	A	B	C	D	E
Viscosity					
77°F, poises X10^6	3.55	1.55	1.70	1.11	2.25
140°F, poises	2242	3012	2183	1812	1911
275°F, poises	6.42	5.33	3.22	4.09	3.10
Penetration					
39.2°F, dmm, 200 gm, 60 sec	13	26	18	26	13
77°F, dmm, 100 gm, 5 sec	61	64	58	81	45
Softening Point, °F	123	125	121	122	119
Thin Film Oven Residue					
Percent Loss	0	0.04	0.05	0.08	0.15
Viscosity, 140°F, poises	4681	5008	4017	3236	4285
Penetration, 77°F, dmm	41	53	32	56	32
Rolling Thin Film Oven Residue					
Percent Loss	0	0	0	0.11	0.18
Viscosity, 140°F, poises	5180	7350	5356	6369	5345
Penetration, 77°F, dmm	32	50	24	42	29

Table B2. Physical Properties of the Experimental AC-10 Grade Asphalt Cements.

	A	B	C	D	E
Viscosity					
77° F, poises X10^6	0.66	0.22	0.66	0.50	0.88
140 °F, poises	973	773	1268	931	955
275 °F, poises	2.76	2.76	2.85	3.18	2.34
Penetration					
39.2 F, dmm, 200gm, 60 sec	20	35	16	35	17
77 F, dmm, 100 gm, 5 sec	106	166	80	113	80
Softening Point, °F	111	106	114	116	115
Thin Film Oven Residue					
Percent Loss	0	0.04	0.03	0.13	0.37
Viscosity, 140 °F, poises	1280	1210	2539	2381	2436
Penetration, 77°F, dmm	69	121	50	68	42
Rolling Thin Film Oven Residue					
Percent Loss	0	0	0	0.01	0.51
Viscosity, 140°F, poises	1663	1608	2911	2865	4886
Penetration, 77°F, dmm	62	113	37	59	28

Table B3. Physical Properties of the Virgin Asphalt Cements Delivered to the Dickens, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77 °F poises X10^6	140 °F	275 °F	39.2 °F 200g, 60s	77 °F 100g, 5s
A	AC-20	4.00	2175	7.15	8	65
A	AC-10	1.35	1220	4.51	15	95
B	AC-20	1.20	2523	4.64	27	77
C	AC-20	2.75	2576	3.55	7	43
D	AC-20	2.50	2151	4.53	22	69
E	AC-20	1.90	1515	2.87	9	53
E	AC-10	1.15	1264	2.55	15	72

Table B4. Physical Properties of the Thin Film Oven Residue of the Virgin Asphalt Cements Delivered to the Dickens, Texas, Site.

Asphalt Producer	Asphalt Grade	Percent Loss	Viscosity, poises 140°F	Penetration, dmm 77°F
A	AC-20	0	3536	45
A	AC-10	0.02	2477	55
B	AC-20	0.14	5285	53
C	AC-20	0	5223	28
D	AC-20	0.01	5169	45
E	AC-20	0.04	5006	27
E	AC-10	0.22	2673	41

Table B5. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Laboratory Compacted from Dickens, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140°F	275°F	39.2°F 200 gm, 60 sec	77°F 100g, 5s
A	AC-20	18.4	9564	11.03	14	20
A	AC-10	12.0	2000	5.93	21	62
B	AC-20	7.0	11250	8.30	20	38
C	AC-20	16.0	8668	6.06	8	21
D	AC-20	1.40	11355	8.74	21	32
E	AC-20	14.0	4750	4.49	9	29
E	AC-10	1.3	4322	4.16	8	28

Table B6. Physical Properties of the Asphalt Cement Recovered from Cores after One Year Service from Dickens, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140 °F	275° F	39.2°F 200gm, 60sec	77°F 100g, 5s
A	AC-20	12.0	12300	11.76	5	25
A	AC-10	17.0	12439	7.29	15	37
B	AC-20	21.0	9787	5.67	3	17
C	AC-20	8.0	5523	8.08	8	32
D	AC-20	21.0	8670	5.79	2	20
E	AC-20	30.0	15466	7.45	0	18
E	AC-10	18.5	23115	9.70	10	21

Table B7. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Field Compacted Samples from Dickens, Texas after Two Years Service.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		$77^{o}F$ poises x 10^{6}	$140^{o}F$	$275^{o}F$	$39.2^{o}F$ 200g, 60s	$77^{o}F$ 100g, 5s
A	AC-10	13.0	8418	6.65	12	31
A	AC-20	18.5	11.2	10.26	16	27
B	AC-20	19.0	18.7	9.90	13	28
C	AC-20	20.5	13816	9.00	12	26
D	AC-20	29.0	15.0	7.79	3	17
E	AC-10	33.0	10682	5.94	5	16
E	AC-20	40.0	17.1	7.54	2	16

Table B8. Physical Properties of the Virgin Asphalt Cements Delivered to the Dumas, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-20	1.90	2155	6.39	16	61
A	AC-10	0.56	958	4.65	16	104
B	AC-10	0.36	961	3.63	39	133
C	AC-10	0.83	1388	3.06	15	74
D	AC-10	0.53	1030	3.21	30	105
E	AC-20	1.60	2354	3.17	10	54
E	AC-10	0.97	1038	2.48	16	71

Table B9. Physical Properties of the Thin Film Oven Residue of the Virgin Asphalt Cements Delivered to the Dumas, Texas, Site.

Asphalt Producer	Asphalt Grade	Percent Loss	Viscosity, poises 140°F	Penetration, dmm 77°F
A	AC-20	0.02	4344	44
A	AC-10	0.07	2053	67
B	AC-10	0.05	2057	86
C	AC-10	0.14	2716	47
D	AC-10	0.05	2592	63
E	AC-20	0.12	4016	32
E	AC-10	0.02	2502	41

Table B10. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Laboratory Compacted from Dumas, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77 F poises $X10^6$	140 F	275 F	39.2 F 200gm, 60 sec	77 F 100g, 5s
A	AC-20	3.4	2984	7.13	12	51
A	AC-10	1.6	1723	5.24	20	75
B	AC-10	0.56	1360	3.49	57	107
C	AC-10	2.9	2995	3.86	7	45
D	AC-10	1.5	1989	3.98	26	66
E	AC-20	5.0	2374	3.42	12	41
E	AC-10	2.0	1943	3.08	12	47

Table B11. Physical Properties of the Asphalt Cement Recovered from Cores after One Year Service from Dumas, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140°F	275°F	39.2°F 200gm, 60sec	77°F 100g, 5s
A	AC-20	5.8	4468	8.41	10	41
A	AC-10	2.0	2263	4.81	15	57
B	AC-10	0.7	1453	3.59	30	90
C	AC-10	2.06	2477	4.41	15	62
D	AC-10	1.28	1930	4.04	26	71

Table B12. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Field Compacted Samples from Dumas, Texas after Two Years Service.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises x 10^6	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-10	1.2	2573	6.89	16	62
A	AC-20	8.8	7511	10.20	12	43
B	AC-10	2.0	2106	4.58	83	25
D	AC-10	3.2	2625	4.94	18	64
E	AC-10	3.9	4244	4.50	5	30
E	AC-20	50.0	36230	7.13	5	20

Table B13. Physical Properties of the Virgin Asphalt Cements Delivered to the Lufkin, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140°F	275°F	39.2°F 200gm, 60s	77°F 100g, 5s
A	AC-20	1.80	1728	5.05	16	70
B	AC-10	0.76	932	3.63	25	95
C	AC-20	1.55	1811	3.19	6	64
D	AC-20	0.96	1913	3.96	23	79
D	AC-10	0.42	1040	2.88	33	111
E	AC-20	1.90	1858	2.82	10	58

Table B14. Physical Properties of the Thin Film Oven Residue of the Virgin Asphalt Cements Delivered to the Lufkin, Texas, Site.

Asphalt Producer	Asphalt Grade	Percent Loss	Viscosity, poises 140° F	Penetration, dmm 77° F
A	AC-20	0.28	4534	46
B	AC-20	1.08	4003	45
C	AC-20	0.08	3867	34
D	AC-20	0.07	4210	47
D	AC-10	1.23	4600	30
E	AC-20	0.47	3360	52

Table B15. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Laboratory Compacted from Lufkin, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77 °F poises X10^6	140°F	275° F	39.2°F 200 gm, 60s	77°F 100g,5s
A	AC-20	4.5	3781	7.45	15	52
B	AC-20	3.45	3600	5.46	22	57
C	AC-20	3.3	2939	4.40	9	48
D	AC-20	4.1	5940	5.77	5	45
D	AC-10	1.28	1866	3.90	19	73
E	AC-20	9.0	4307	4.25	4	28

Table B16. Physical Properties of the Asphalt Cement Recovered from Cores after One Week Service from Lufkin, Texas, Site.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises X10^6	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-20	3.55	3735	6.92	10	48
B	AC-10	3.70	3891	6.26	7	56
C	AC-20	3.80	2754	3.87	10	46
D	AC-20	3.80	2975	4.98	12	52
D	AC-10	1.20	2418	4.44	16	63
E	AC-20	14.50	8790	5.06	4	23

Table B17. Physical Properties of the Asphalt Cement Recovered from Field Mixed, Field Compacted Samples from Lufkin, Texas after One Year Service.

Asphalt Producer	Asphalt Grade	Viscosity, poises			Penetration, dmm	
		77°F poises x 10^6	140°F	275°F	39.2°F 200g, 60s	77°F 100g, 5s
A	AC-20	4.8	5553	1.21	0	20
B	AC-10	23.0	8666	6.69	3	20
C	AC-20	26.0	8970	6.16	0	15
D	AC-10	2.3	1866	3.99	17	68
D	AC-20	24.0	8400	6.40	0	19
E	AC-20	7.1	5190	6.34	9	38

APPENDIX C

Results of the Asphaltic Mixture Tests

Table C1. Properties of Field Mixed, Laboratory Compacted Specimens from the Dickens, Texas Site.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	4.9	5.5	2.27	1.76	0.579	0.123	38	1600	17	117	0.0069	17,800
A	AC-10	5.1	4.1	2.39	1.59	0.342	0.053	39	1300	14	86	0.0100	8,500
B	AC-20	5.7	5.8	1.88	1.17	0.374	0.100	42	1600	18	102	0.0033	31,500
C	AC-20	5.2	6.3	2.29	1.66	0.666	0.238	40	2000	17	159	0.0036	44.400
D	AC-20	5.7	4.7	2.24	1.34	0.501	0.117	40	2100	16	122	0.0035	35,000
E	AC-20	5.2	6.7	2.16	1.63	0.603	0.130	40	1600	21	140	0.0082	17,100
E	AC-10	4.5	5.1	1.97	1.45	0.512	0.092	40	1600	15	131	0.0091	14,500

Table C2. Properties of Field Mixed, Laboratory Compacted Specimens from the Dickens, Texas Site.

				After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
Source	Grade	Asphalt Content, Percent	Air Voids, Percent	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	4.9	5.5	0.451	33	116	0.0059	21,600	0.246	40	121	0.0081	15,200
A	AC-10	5.1	4.1	0.309	26	70	0.0107	6,500	0.239	41	84	0.0127	7,100
B	AC-20	5.7	5.8	0.303	26	73	0.0041	17,900	0.133	44	92	0.0049	19,700
C	AC-20	5.2	6.3	0.632	34	165	0.0043	38,300	0.526	31	166	0.0054	30,700
D	AC-20	5.7	4.7	0.447	31	112	0.0042	27,700	0.347	29	112	0.0058	19.700
E	AC-20	5.2	6.7	0.497	36	120	0.0071	17,000	0.425	44	90	0.0090	9,900
E	AC-10	4.5	5.1	0.423	36	101	0.0083	12,200	0.435	43	116	0.0118	9,600

Table C3. Properties of Field Mixed, Field Compacted Samples from the Dickens, Texas Site After One Year Service.

				After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
Source	Grade	Asphalt Content, Percent	Air Voids, Percent	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.9	10.0	0.188	20	35	0.0032	19,000	0.186	34.6	41	0.0036	13,400
A	AC-10	5.0	14.3	0.104	20	18	0.0026	6,900	0.112	22.3	25	0.0035	4,200
B	AC-20	6.0	9.9	0.174	25	21	0.0028	8,000	0.295	30.7	48	0.0032	25,800
C	AC-20	6.2	9.9	0.159	28	33	0.0040	10,700	0.183	34.4	57	0.0040	14,400
D	AC-20	5.0	14.1	0.150	28	17	0.0026	7,300	0.235	33.4	32	0.0016	21,100
E	AC-20	5.3	10.5	0.210	22	45	0.0010	43,900	0.245	34.2	55	0.0011	49,100
E	AC-10	4.2	14.5	0.128	24	15	0.0016	11,300	0.057	17.1	11	0.0058	2,100

Table C4. Properties of Field Mixed, Field Compacted Samples from the Dickens, Texas Site After One Year Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.9	10.0	1.73	0.970	0.262	0.048	26.4	934	14	51	0.0060	8,600
A	AC-10	5.0	14.3	1.30	0.804	0.232	0.076	24.0	1121	11	76	0.0035	22,000
B	AC-20	6.0	9.9	2.33	1.31	0.345	0.064	26.5	1068	11	107	0.0036	31,100
C	AC-20	6.2	9.9	2.13	1.20	0.197	0.044	27.3	1093	11	83	0.0056	15,300
D	AC-20	5.0	14.1	1.87	1.25	0.318	0.062	33.0	941	14	94	0.0033	28,800
E	AC-20	5.3	10.5	1.68	1.29	0.388	0.084	28.1	1220	10	93	0.0024	39,700
E	AC-10	4.2	14.5	1.47	0.686	0.144	0.034	21.2	1012	13	54	0.0438	1,270

Table C5. Properties of Field Mixed, Field Compacted Samples from the Dickens, Texas Site After Two Years Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.6	12.7	2.16	1.51	0.434	0.155	28	1700	14	113	0.0025	46,300
A	AC-10	5.4	9.1	2.13	1.45	0.424	0.120	30	1700	11	109	0.0029	37,000
B	AC-20	5.2	14.0	2.13	0.995	0.356	0.114	35	1700	10	80	0.0027	32,200
C	AC-20	5.7	13.6	1.56	1.12	0.451	0.157	30	1700	16	107	0.0025	43,500
D	AC-20	5.2	13.0	2.32	1.40	0.557	0.141	29	1800	11	140	0.0028	52,500
E	AC-20	4.4	12.3	1.63	1.30	0.510	0.203	25	1600	10	142	0.0022	64,600
E	AC-10	4.9	10.6	1.77	1.33	0.536	0.177	26	1700	11	159	0.0024	67,700

Table C6. Properties of Field Mixed, Field Compacted Samples from the Dickens, Texas Site After Two Years Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	After Accelerated Lottman Procedure					After Seven Day Soak				
				M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test			M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test		
						Stress, psi	Strain, in/in	Modulus, psi			Stress, psi	Strain, in/in	Modulus psi
A	AC-20	5.6	12.7	0.098	27	27	0.0011	24,900	0.191	26	237	0.0029	84,300
A	AC-10	5.4	9.1	0.0271	31	60	0.0012	53,300					
B	AC-20	5.2	14.0	0.027	19	11	0.0018	6,000					
C	AC-20	5.7	13.6	0.022	16	12	0.0014	8,100	0.122	19	169	0.0034	50,400
D	AC-20	5.2	13.0	0.306	27	51	0.00051	103,000	0.318	29	62	0.00089	78,000
E	AC-20	4.4	12.3	0.107	17	18	0.00053	26,900					
E	AC-10	4.9	10.6	0.287	22	43	0.00046	96,000					

Table C7. Properties of Field Mixed, Laboratory Compacted Samples from the Dumas, Texas Site.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.4	6.6	1.93	1.46	0.450	0.138	46	1900	16	100	0.0037	27,300
A	AC-10	6.2	5.5	1.81	1.36	0.318	0.072	40	1400	15	63	0.0049	12,900
B	AC-10	5.3	8.5	2.02	1.66	0.285	0.080	47	2500	18	73	0.0046	15,700
C	AC-10	5.7	10.7	2.21	1.35	0.416	0.122	45	1700	15	104	0.0033	32,500
D	AC-10	5.7	7.5	1.79	1.26	0.318	0.099	46	1600	15	86	0.0038	23,000
E	AC-20	5.6	8.6	1.93	1.39	0.561	0.148	48	2000	16	140	0.0038	38,200
E	AC-10	5.8	6.1	1.87	1.676	0.519	0.141	46	1700	16	126	0.0044	28,800

Table C8. Properties of Field Mixed, Laboratory Compacted Samples from the Dumas, Texas Site.

				After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
Source	Grade	Asphalt Content, Percent	Air Voids, Percent	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.4	6.6	0.227	8	60	0.0055	11,100	0.282	9	52	0.0081	6,700
A	AC-10	6.2	5.5	0.297	9	63	0.0049	12.900	0.265	10	67	0.0073	9,300
B	AC-10	5.3	8.5	0.089	22	49	0.0096	5,200	0.038	17	32	0.0128	2,500
C	AC-10	5.7	10.7	0.137	25	47	0.0059	11,600	0.030	24	19	0.0103	1,900
D	AC-10	5.7	7.5	0.079	7	41	0.0081	5,200	0.056	5	28	0.0107	3,100
E	AC-20	5.6	8.6	0.216	12	80	0.0049	16,100	0.183	12	42	0.0062	7,200
E	AC-10	5.8	6.1	0.244	12	84	0.0052	16,400	0.270	21	52	0.0057	9,200

Table C9. Properties of Field Mixed, Field Compacted Samples from the Dumas, Texas Site After One Week Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	After Accelerated Lottman Procedure					After Seven Day Soak				
				M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test			M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test		
						Stress, psi	Strain, in/in	Modulus, psi			Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.5	13.9	0.061		22	0.0141	1600	0.064	16			
A	AC-10	4.0	20.4	0.022		6	0.0170	400	0.033	11			
B	AC-10	5.7	12.2	0.074		27	0.0098	2700	0.088	20			
C	AC-10	5.1	16.5	0.039		18	0.0163	1100	0.056	15			
D	AC-10	6.2	12.6	0.034		20	0.0218	900	0.046	11			
E	AC-20	4.3	17.1	0.010		6	0.0196	300	0.019	11			
E	AC-10	5.3	20.4	0.016		6	0.0182	300	0.025	11			

Table C10. Properties of Field Mixed, Field Compacted Samples from the Dumas, Texas Site After One Week Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.5	13.9	1.43	0.815	0.155	0.019	25	400	29	47	0.0116	4,100
A	AC-10	4.0	20.4	0.901	0.624	0.082	0.012	18	200	15	19	0.0069	2,800
B	AC-10	5.7	12.2	1.32	1.03	0.230	0.034	24	500	17	21	0.0092	2,300
C	AC-10	5.1	16.5	1.16	0.697	0.110	0.015	20	200	17	34	0.0105	3,200
D	AC-10	6.2	12.6	0.996	0.593	0.080	0.012	18	400	18	33	0.0148	2,200
E	AC-20	4.3	17.1	1.11	0.475	0.042	0.011	11	300	13	17	0.0098	1,700
E	AC-10	5.3	10.4	0.728	0.335	0.046	0.009	10	200	13	16	0.0102	1,800

Table C11. Properties of Field Mixed, Field Compacted Samples from the Dumas, Texas Site After One Year Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	After Accelerated Lottman Procedure					After Seven Day Soak				
				M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test			M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test		
						Stress, psi	Strain, in/in	Modulus, psi			Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	11.6	0.078	23	38	0.0045	9,300	0.090	21.5	35	0.0055	6,300
A	AC-10	6.0	6.2	0.059	20	31	0.0120	2,700	0.086	23.2	49	0.0071	6,700
B	AC-10	4.0	13.7	0.023	18	77	0.0065	12,200	0.032	-	24	0.0063	3,800
C	AC-10	5.4	15.4	0.023					0.037	23.4	13	0.0068	2,400
D	AC-10	5.0	12.2	0.033	23	18	0.0058	3,100	0.037	23.4	23	0.0056	4,200
E	AC-20	5.2	10.5	0.200	28	64	0.0026	25,300	0.161	32.2	57	0.0040	14,000
E	AC-10	5.3	13.8	0.178	21	64	0.0024	27,800	0.125	19.7	41	0.0039	10,600

Table C12. Properties of Field Mixed, Field Compacted Samples from the Dumas, Texas Site After One Year Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	11.6	1.73	1.12	0.369	0.086	30.5	1000	13	86	0.0027	32,400
A	AC-10	6.0	6.2	1.60	0.958	0.151	0.033	25.5	1100	14	75	0.0060	12,500
B	AC-10	4.0	13.7	1.54	0.811	0.134	0.027	34.7	1000	12	50	0.0038	13,200
C	AC-10	5.4	15.4	1.32	0.918	0.195	0.039	28.9	1000	11	70	0.0038	18,300
D	AC-10	5.0	12.2	1.83	1.05	0.315	0.097	38.0	1400	10	77	0.0025	31,800
E	AC-20	5.2	10.5	1.68	1.29	0.388	0.084	32.7	600	10	92	0.0024	39,700
E	AC-10	5.3	13.8	1.77	1.23	0.440	0.087	30.2	1000	11	107	0.0025	42,700

Table C13. Properties of Field, Field Compacted Samples from the Dumas, Texas Site After Two Years Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	9.2	1.61	1.24	0.423	0.117	29	1600	10	129	0.0028	46,000
A	AC-10	7.5	2.1	2.10	1.23	0.138	0.067	12	1800	13	107	0.0054	20,700
B	AC-10	4.8	10.5	1.89	1.15	0.254	0.093	38	2000	9	82	0.0030	27,400
C	AC-10												
D	AC-10	5.8	8.6	2.18	1.30	0.263	0.096	39	2200	8	105	0.0029	36,900
E	AC-20	5.1	10.2	1.89	1.36	0.525	0.123	39	2100	9	156	0.0027	58,900
E	AC-10	5.0	7.3	1.79	1.25	0.501	0.138	31	1700	11	146	0.0035	45,700

Table C14. Properties of Field Mixed, Field Compacted Samples from the Dumas, Texas Site After Two Years Service.

				After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
Source	Grade	Asphalt Content, Percent	Air Voids, Percent	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	9.2	0.178	24	55	0.0027	20,700	0.206	28	53	0.0040	13,300
A	AC-10	7.5	2.1						0.242	2	79	0.0060	13,700
B	AC-10	4.8	10.5	0.073	25	37	0.0040	9,800	0.108	32	52	0.0027	19,400
C	AC-10												
D	AC-10	5.8	8.6	0.052	18	27	0.0046	6,300	0.142	21	56	0.0058	9,807
E	AC-20	5.1	10.2	0.264	36	78	0.0020	40,000					
E	AC-10	5.0	7.3	0.164	20	47	0.0017	27,700					

Table C15. Properties of Field Mixed, Laboratory Compacted Samples from the Lufkin, Texas Site.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	7.4	1.52	1.16	0.423	0.074	41.9	1523	11	135	0.0033	40,800
B	AC-10	7.0	2.0	1.59	1.04	0.207	0.062	18.9	1676	13	110	0.0044	25,400
C	AC-20	6.7	4.2	2.06	1.41	0.448	0.107	35.1	1530	11	266	0.0043	64,400
D	AC-20	6.6	3.4	1.89	1.09	0.230	0.055	32.5	1449	11	139	0.0043	32,500
D	AC-10	6.7	3.9	1.75	1.08	0.157	0.047	29.9	1353	11	106	0.0043	25,000
E	AC-20	6.7	3.3	2.17	1.32	0.349	0.071	28.3	1507	11	198	0.0050	39,700

Table C16. Properties of Field Mixed, Laboratory Compacted Samples from the Lufkin, Texas Site.

				After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
Source	Grade	Asphalt Content, Percent	Air Voids, Percent	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	7.4	0.316	33.7	171	0.0047	36,600	0.285	30.7	151	0.0052	29,700
B	AC-10	7.0	2.0	0.242	1.0	122	0.0063	19,700	0.223	2.4	132	0.0058	22,800
C	AC-20	6.7	4.2	0.374	15.8	228	0.0055	41,900	0.632	16.9	282	0.0040	70,300
D	AC-20	6.6	3.4	0.311	27.2	155	0.0050	31,200	0.270	19.9	139	0.0058	23,900
D	AC-20	6.7	3.9	0.241	18.9	154	0.0069	22,300	0.319	14.9	132	0.0058	22,800
E	AC-20	6.7	3.3	0.369	11.5	195	0.0055	35,400	0.381	13.7	183	0.0048	38,800

Table C17. Properties of Field Mixed, Field Compacted Samples from the Lufkin, Texas Site After One Week Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	5.0	8.6	2.41	1.23	0.213	0.025	34.8	800	11	70	0.0038	18,900
B	AC-10	7.0	4.8	2.24	1.27	0.193	0.027	36.9	1250	10	102	0.0040	25,600
C	AC-20	6.7	6.6	1.86	1.83	0.642	0.099	36.8	1105	11	216	0.0037	57,700
D	AC-20	6.6	7.4	2.20	1.15	0.178	0.026	26.5	690	15	81	0.0047	17,500
D	AC-10	6.7	3.2	2.05	1.34	0.302	0.058	39.4	1196	9	112	0.0029	39,500
E	AC-20	6.7	6.5	1.90	1.28	0.354	0.043	24.6	1064	11	149	0.0042	36,000

Table C18. Properties of Field Mixed, Field Compacted Samples from the Lufkin, Texas Site After One Week Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	After Accelerated Lottman Procedure					After Seven Day Soak				
						Indirect Tension Test					Indirect Tension Test		
				M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus, psi	M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Stress, psi	Strain, in/in	Modulus psi
A	AC-20	5.0	8.6	0.197	27.7	90	0.0052	17,300	0.175	37.6	68	0.0043	16,000
B	AC-10	7.0	4.8	0.200	19.2	90	0.0049	18,400	0.179	19.7	89	0.0062	14,600
C	AC-20	6.7	6.6	0.497	29.5	189	0.0043	43,800	0.514	21.7	169	0.0043	39,900
D	AC-20	6.6	7.4	0.193	30.1	97	0.0059	16,600	0.172	18.2	89	0.0069	12,800
D	AC-10	6.7	3.2	0.225	32.4	120	0.0058	12,600	0.212	24.8	123	0.0051	24,600
E	AC-20	6.7	6.5	0.323	4.5	119	0.0058	20,700	0.307	19.1	112	0.0054	20,700

Table C19. Properties of Field Mixed, Field Compacted Samples from the Lufkin, Texas Site After One Year Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	Resilient Modulus, psi x 10^6				Hveem Stability, Percent	Marshall		Indirect Tension Test		
				-13°F	33°F	77°F	104°F		Stability, lbs.	Flow, .01 in.	Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	7.0	2.6	2.50	1.28	0.254	0.072		2205	9	144	0.0033	45,600
B	AC-10	6.3	6.2	2.75	2.05	0.654	0.109		2253	8	245	0.0025	113,500
C	AC-20	6.5	3.0	2.58	1.43	0.204	0.045		1978	8	159	0.0039	41,100
D	AC-20	6.6	2.2	2.24	1.26	0.165	0.040		2232	10	116	0.0051	25,200
D	AC-10	6.8	4.2	2.41	1.64	0.499	0.141		1857	9	190	0.0024	84,900
E	AC-20	6.5	3.2	2.60	1.84	0.509	0.082		2072	9	238	0.0026	93,300

Table C20. Properties of Field Mixed, Field Compacted Samples from the Lufkin, Texas Site After One Year Service.

Source	Grade	Asphalt Content, Percent	Air Voids, Percent	After Accelerated Lottman Procedure					After Seven Day Soak				
				M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test			M_R, 77°F, psi x 10^6	Hveem Stability, Percent	Indirect Tension Test		
						Stress, psi	Strain, in/in	Modulus, psi			Stress, psi	Strain, in/in	Modulus, psi
A	AC-20	7.0	2.6	0.308		147	0.0045	32,900	0.283		135	0.0037	36,700
B	AC-10	6.3	6.2	0.748		200	0.0032	64,000	0.758		217	0.0029	76,100
C	AC-20	6.5	3.0	0.028		133	0.0048	27,800	0.032		109	0.0035	30,600
D	AC-20	6.6	2.2	0.217		115	0.0053	23,100	0.196		117	0.0040	30,000
D	AC-10	6.8	4.2	0.533		142	0.0029	49,600	0.503		179	0.0032	58,100
E	AC-20	6.5	3.2	0.547		212	0.0043	49,400	0.567		222	0.0034	66,100

APPENDIX D

Gel Permeation Chromatography

Chromatograms of the Asphalt Cements

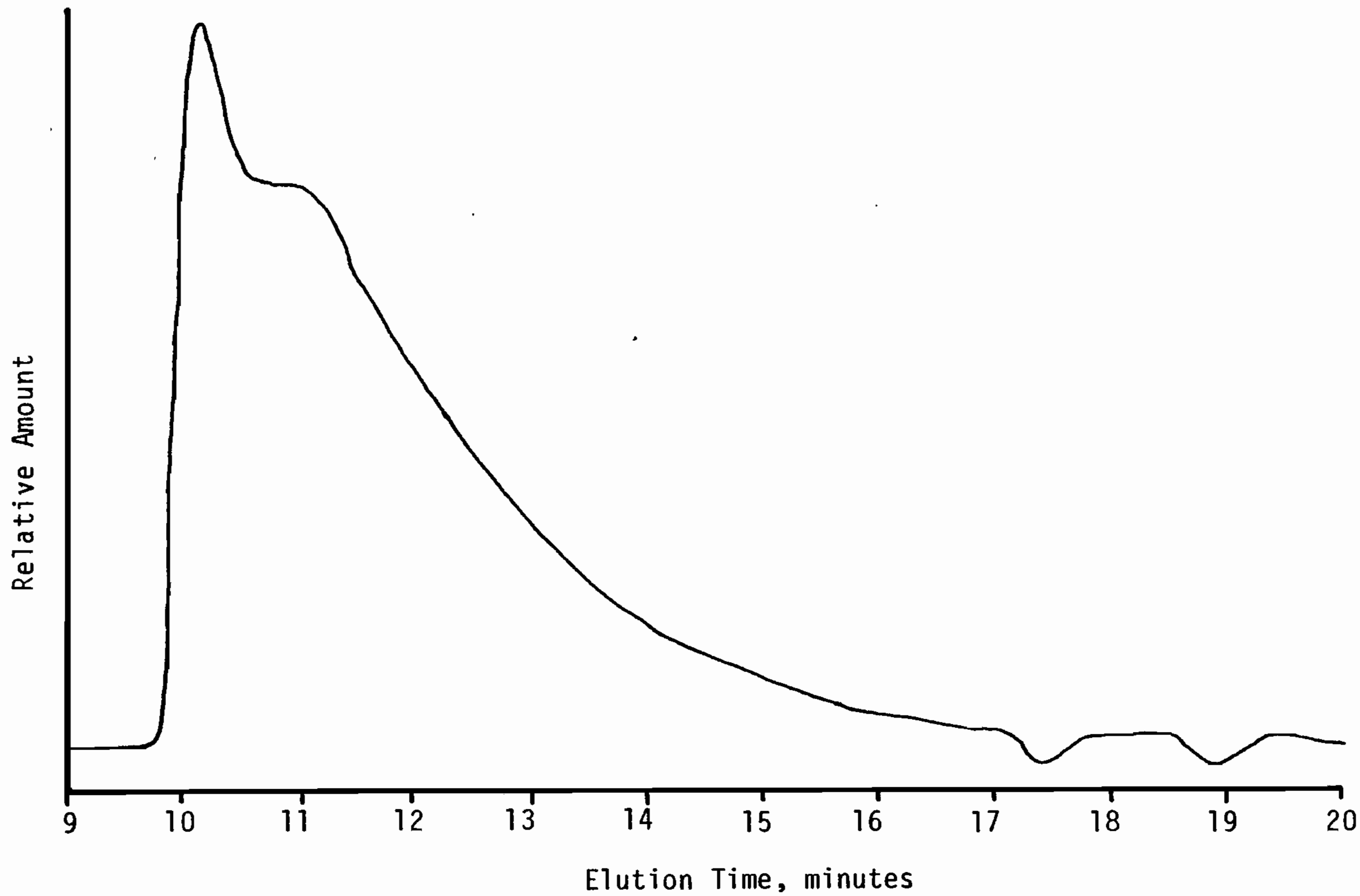

Figure D1. Chromatogram of Asphalt A, AC-10, Virgin Asphalt Cement from the Producer.

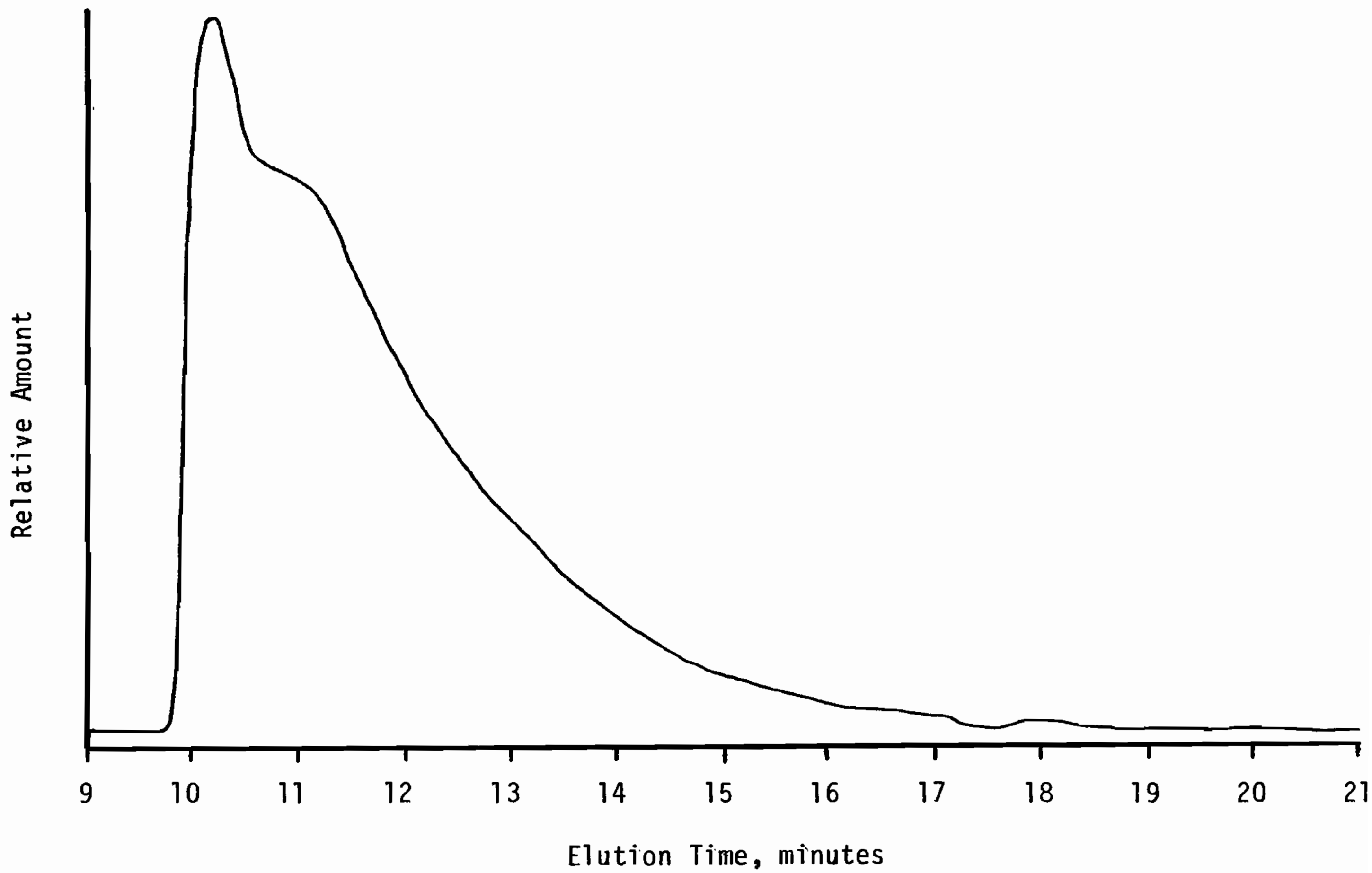

Figure D2. Chromatogram of Asphalt A, AC-20, Virgin Asphalt Cement from the Producer.

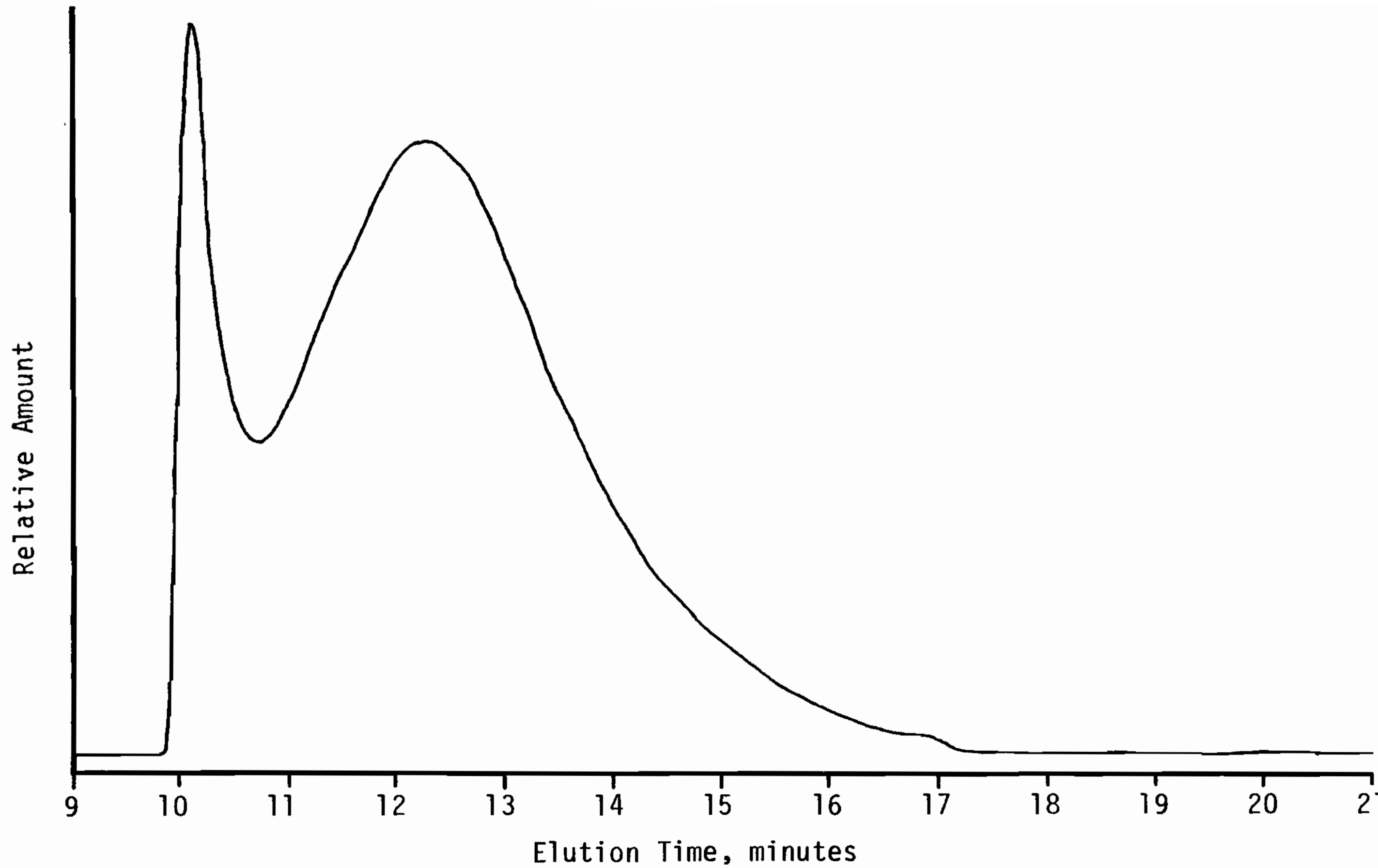

Figure D3. Chromatogram of Asphalt B, AC-10, Virgin Asphalt Cement from the Producer.

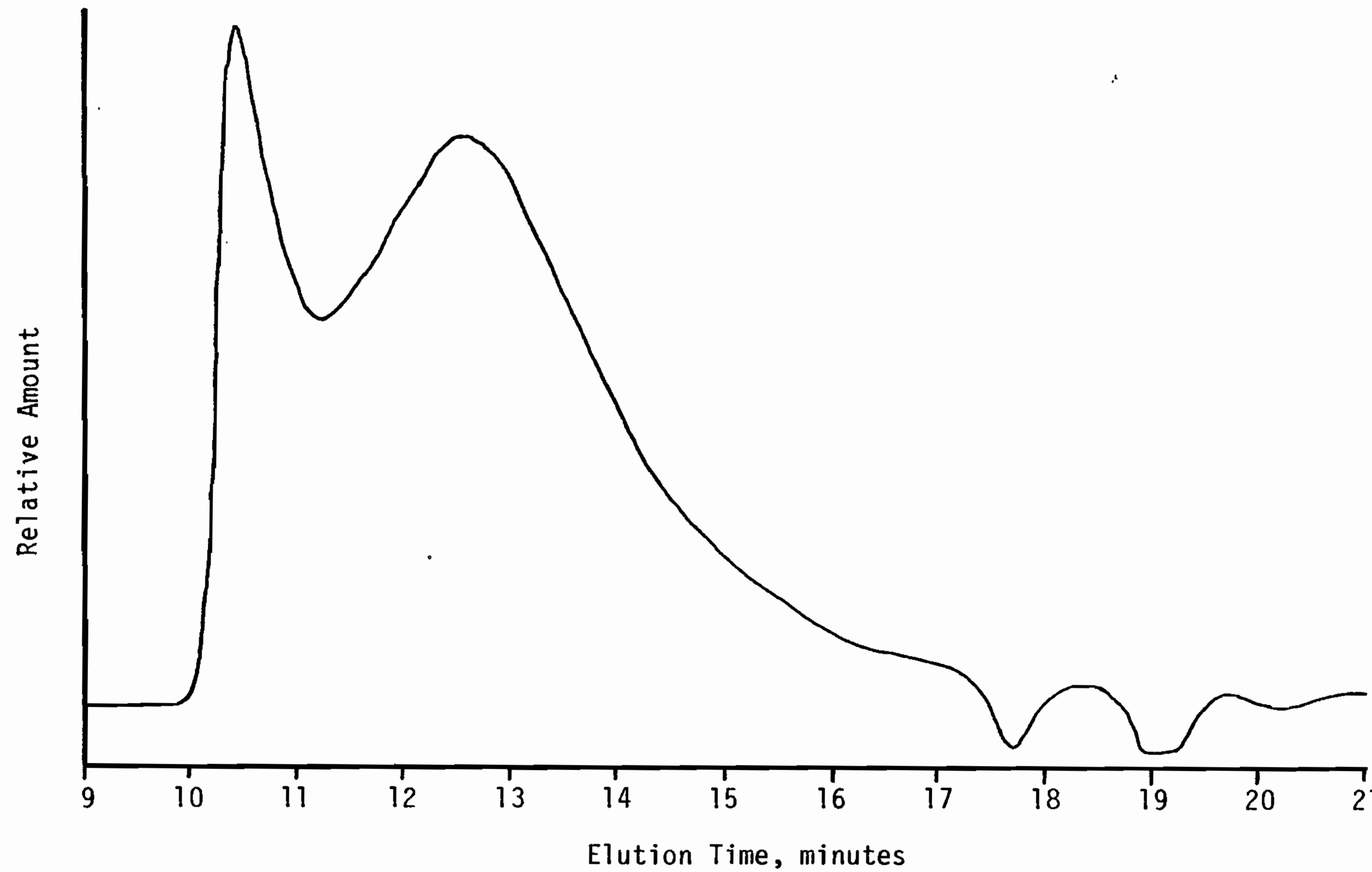

Figure D4. Chromatogram of Asphalt B, AC-20, Virgin Asphalt Cement from the Producer.

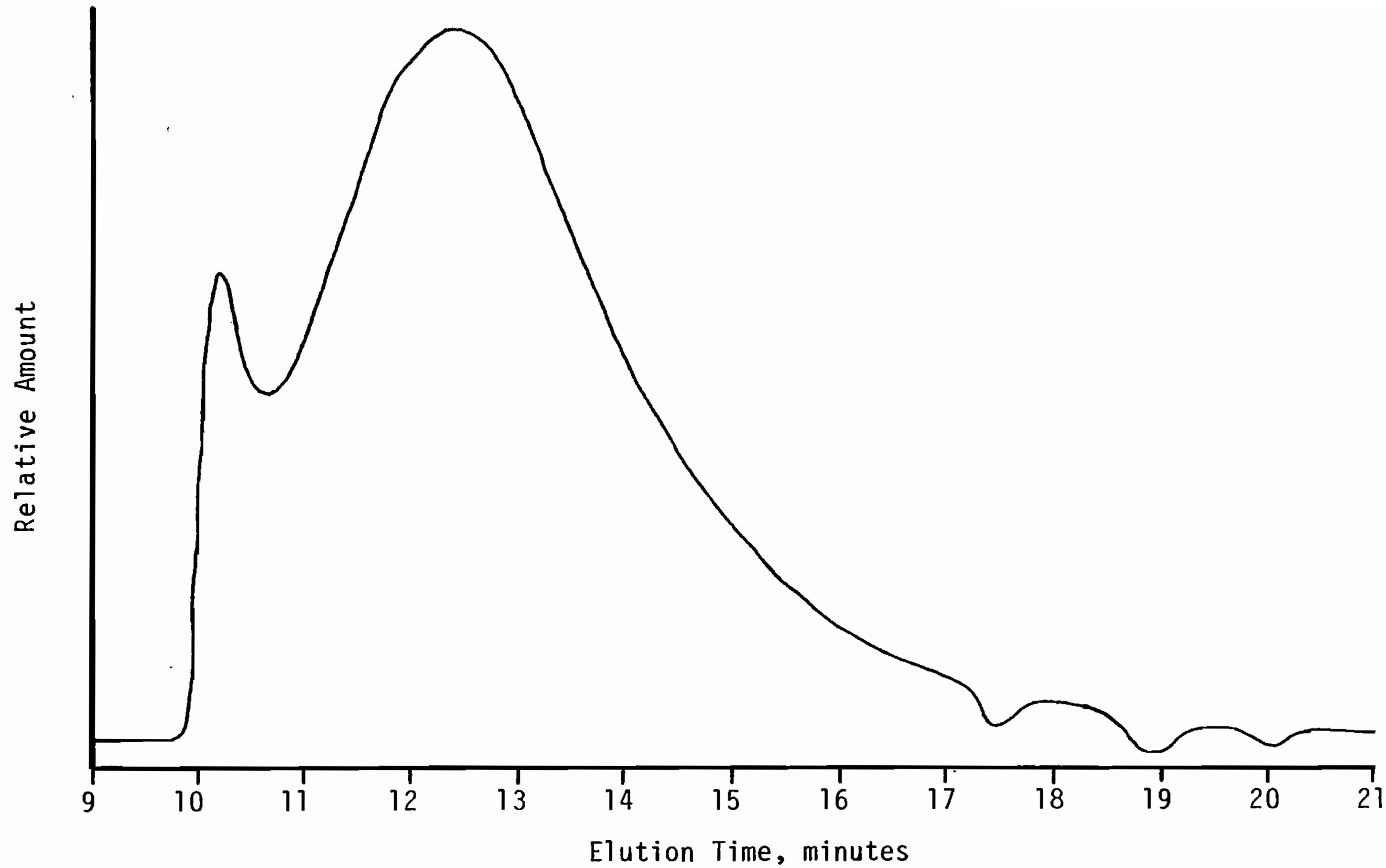

Figure D5. Chromatogram of Asphalt C, AC-10, Virgin Asphalt Cement from the Producer.

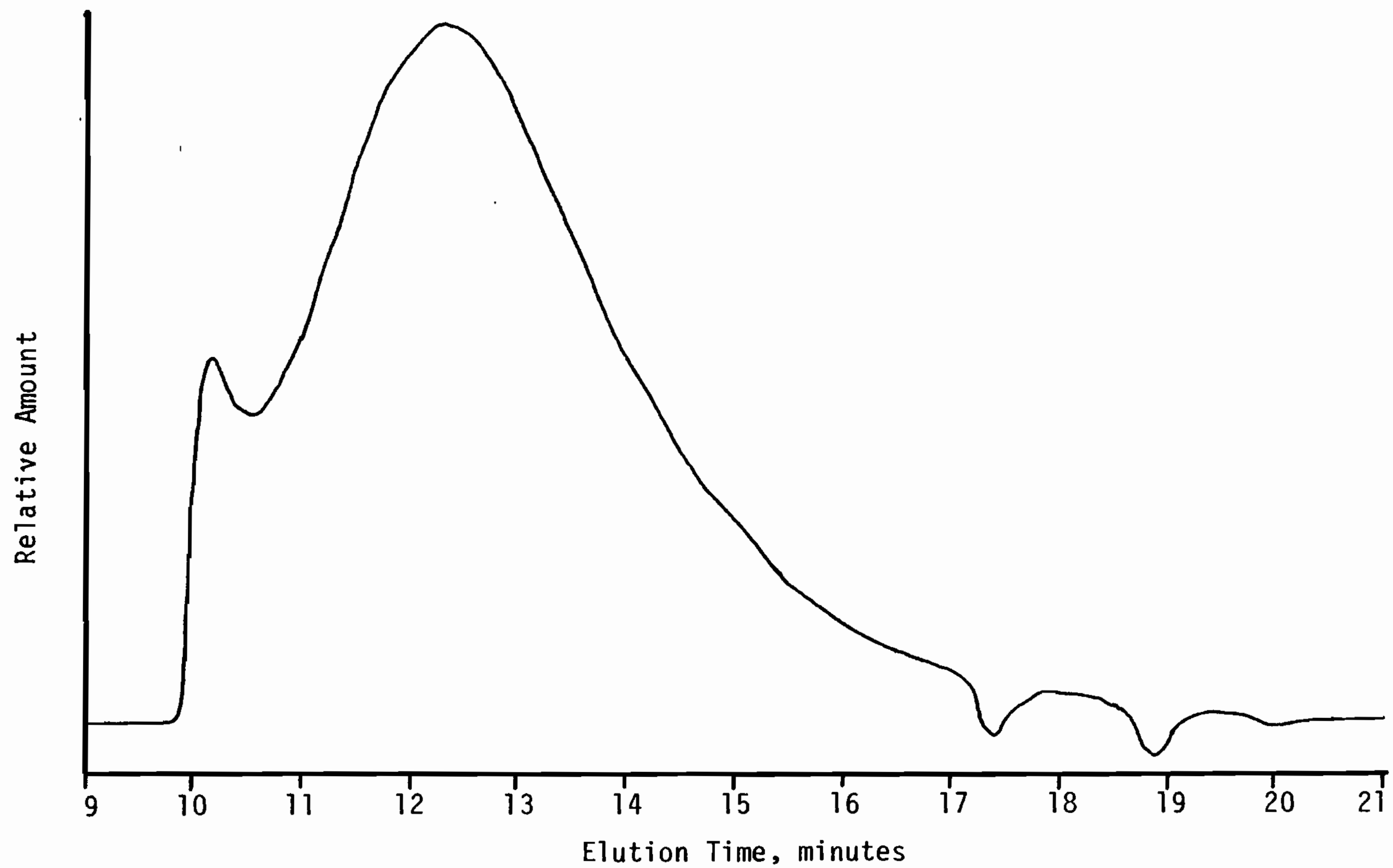

Figure 56. Chromatogram of Asphalt C, AC-20, Virgin Asphalt Cement from the Producer.

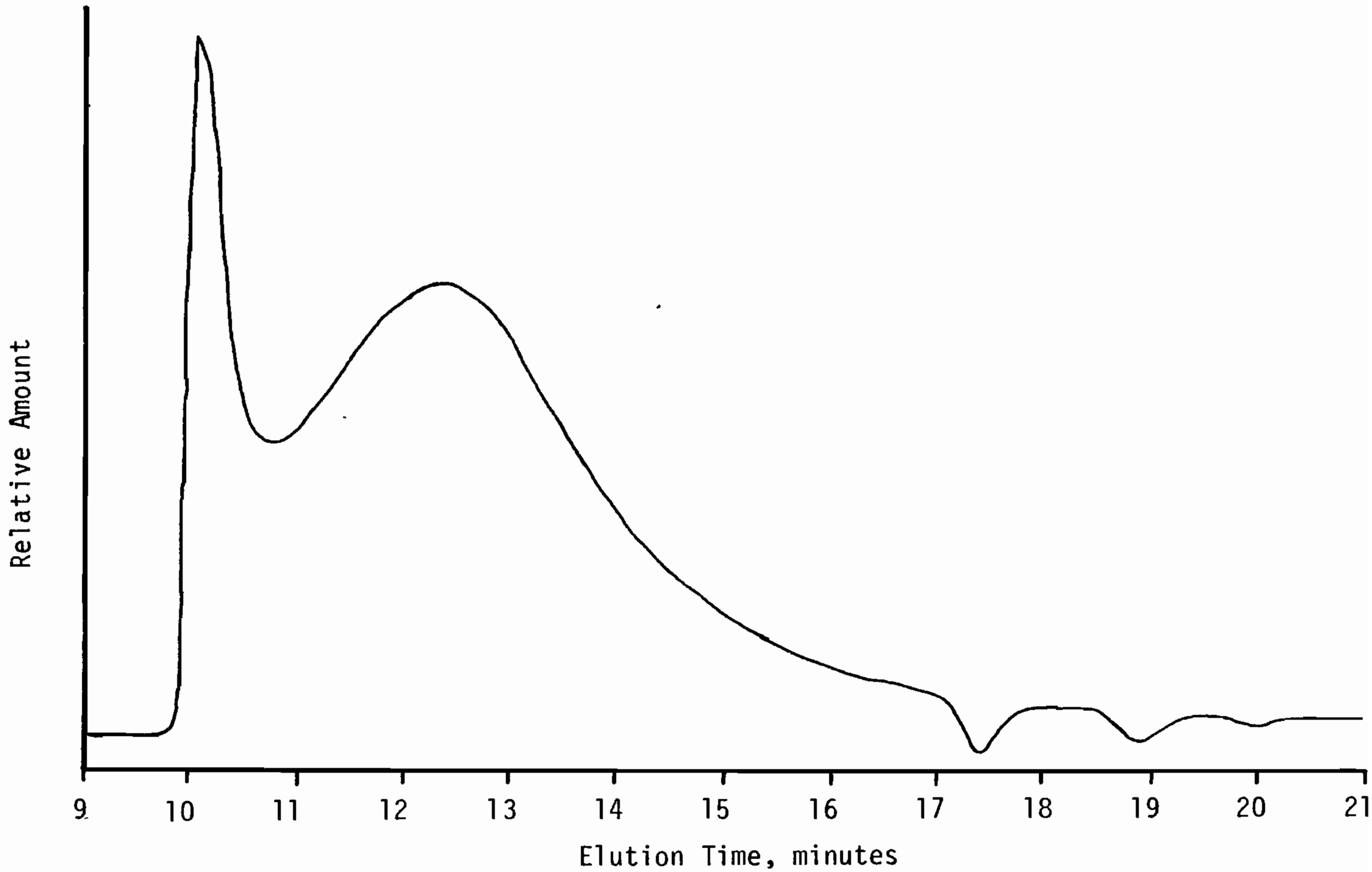

Figure D7. Chromatogram of Asphalt D, AC-10, Virgin Asphalt Cement from the Producer.

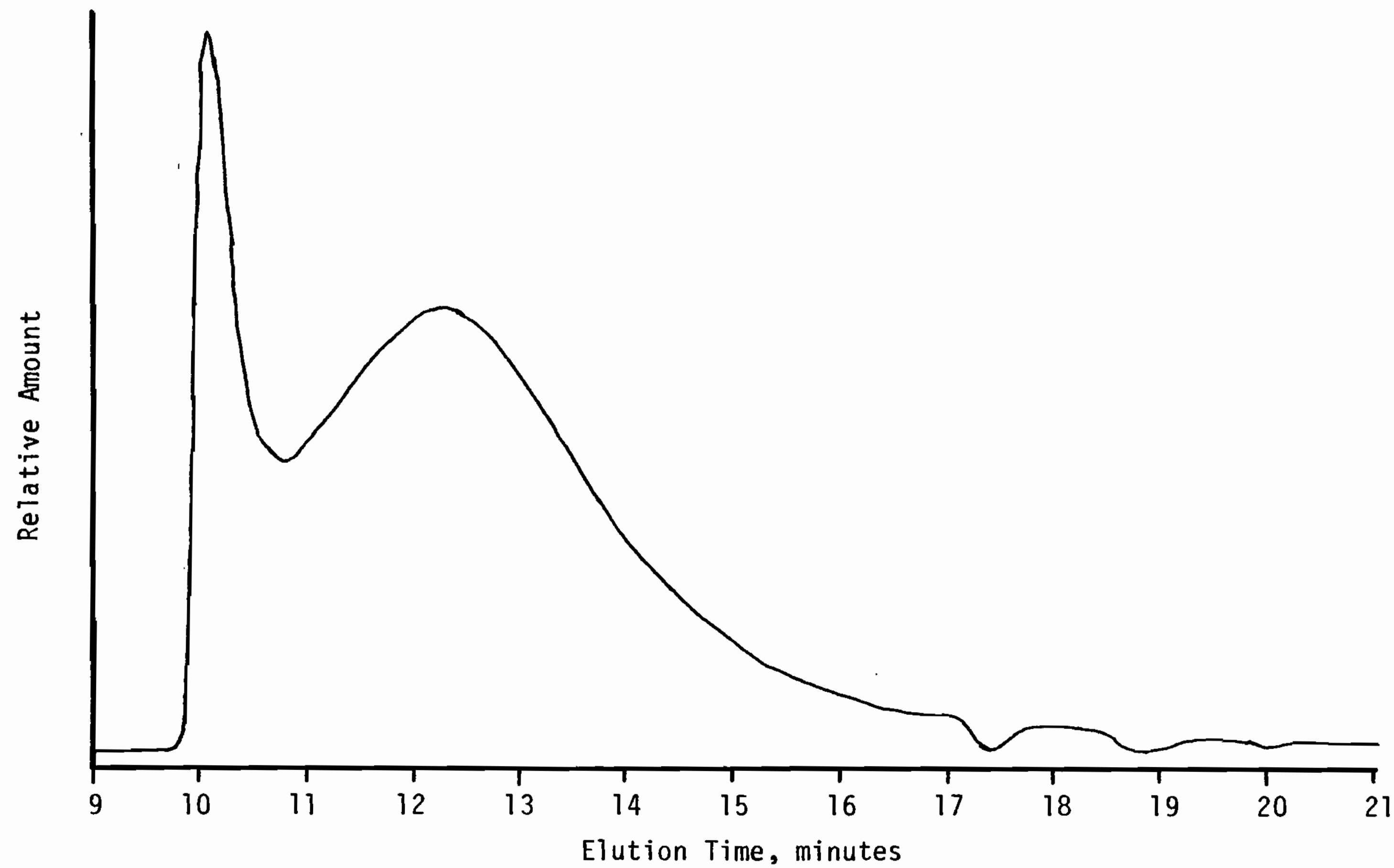

Figure D8. Chromatogram of Asphalt D, AC-20, Virgin Asphalt Cement from the Producer.

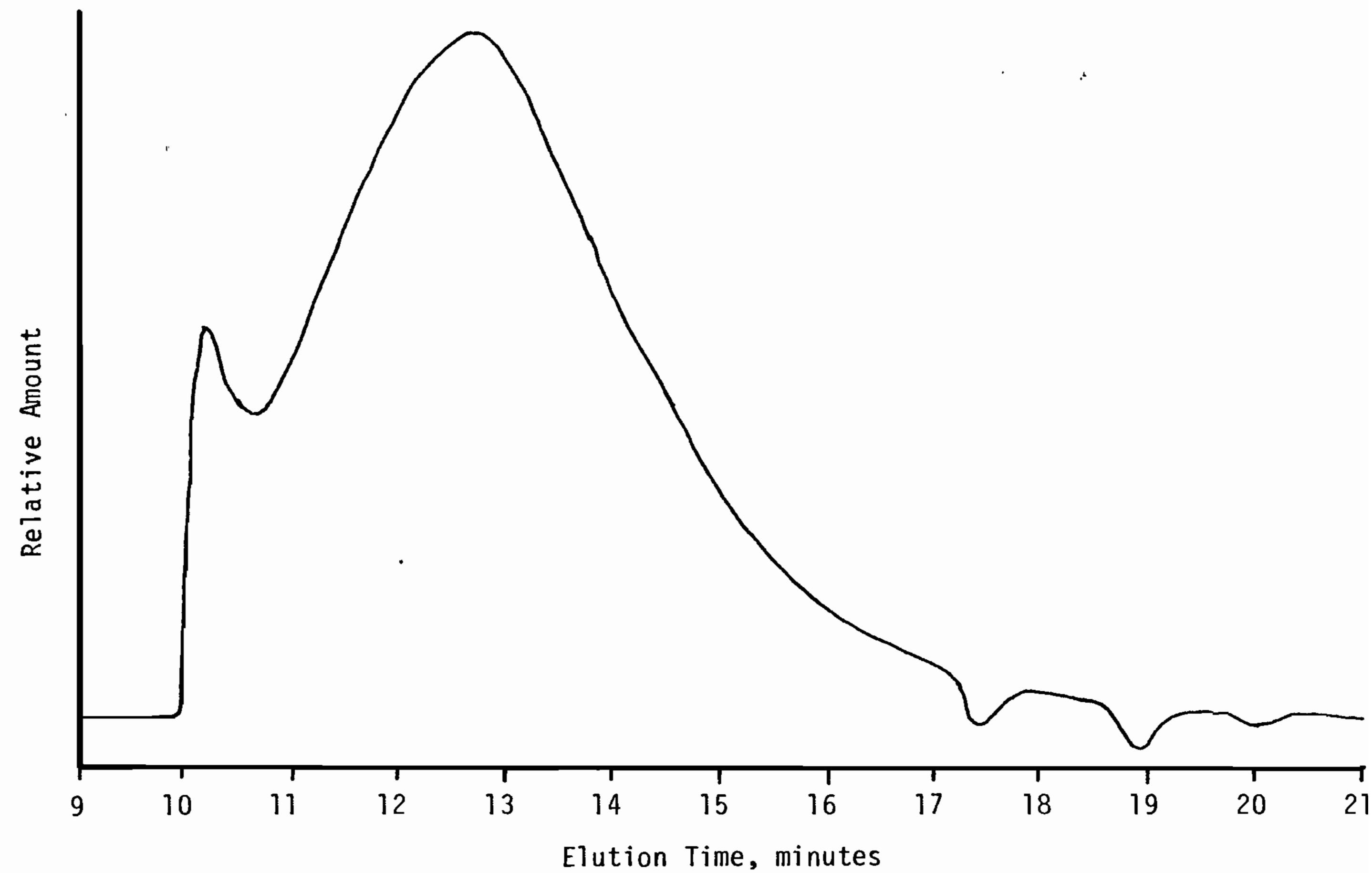

Figure D9. Chromatogram of Asphalt E, AC-10, Virgin Asphalt Cement from the Producer.

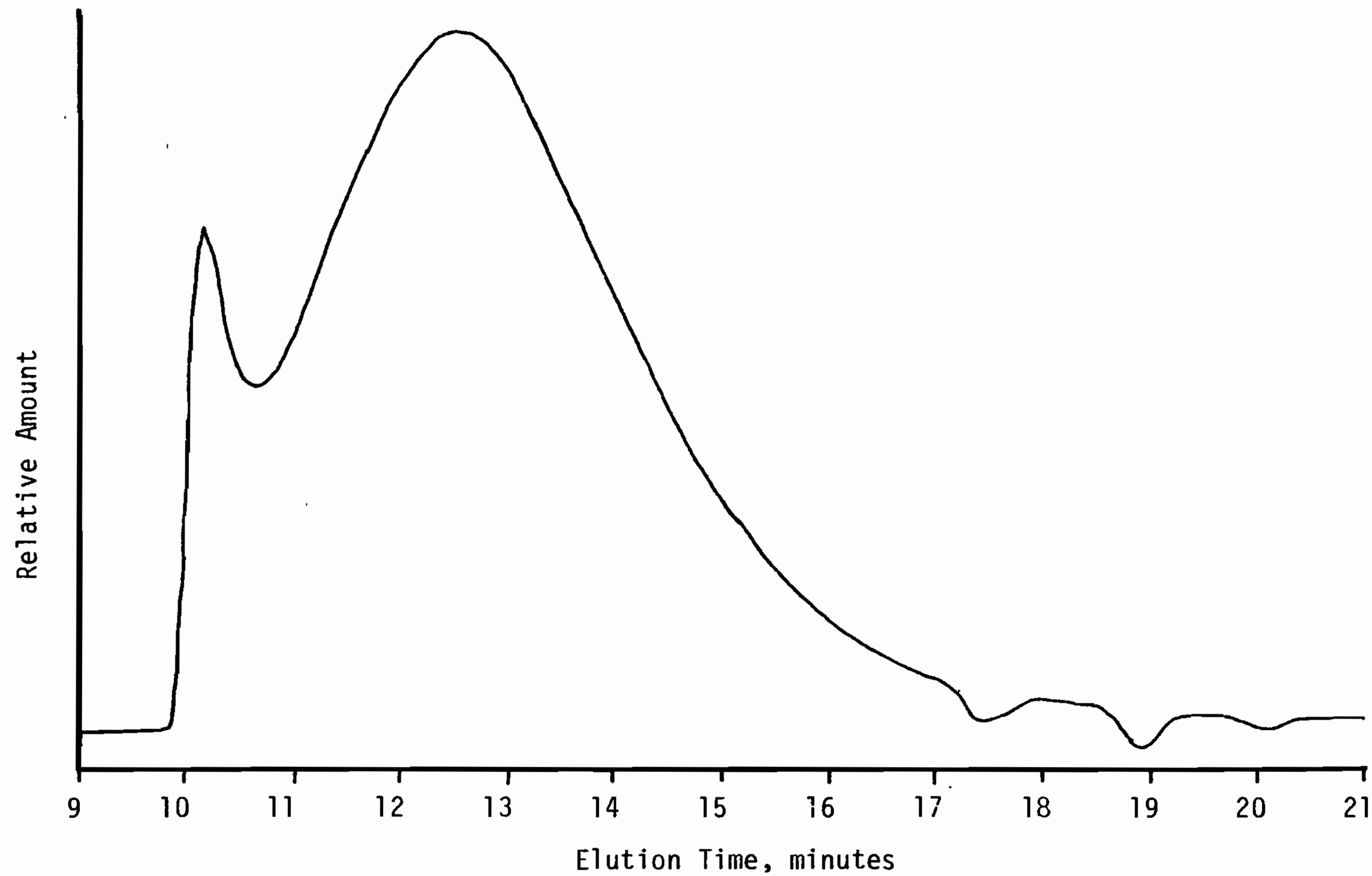

Figure D10. Chromatogram of Asphalt E, AC-20, Virgin Asphalt Cement from the Producer.

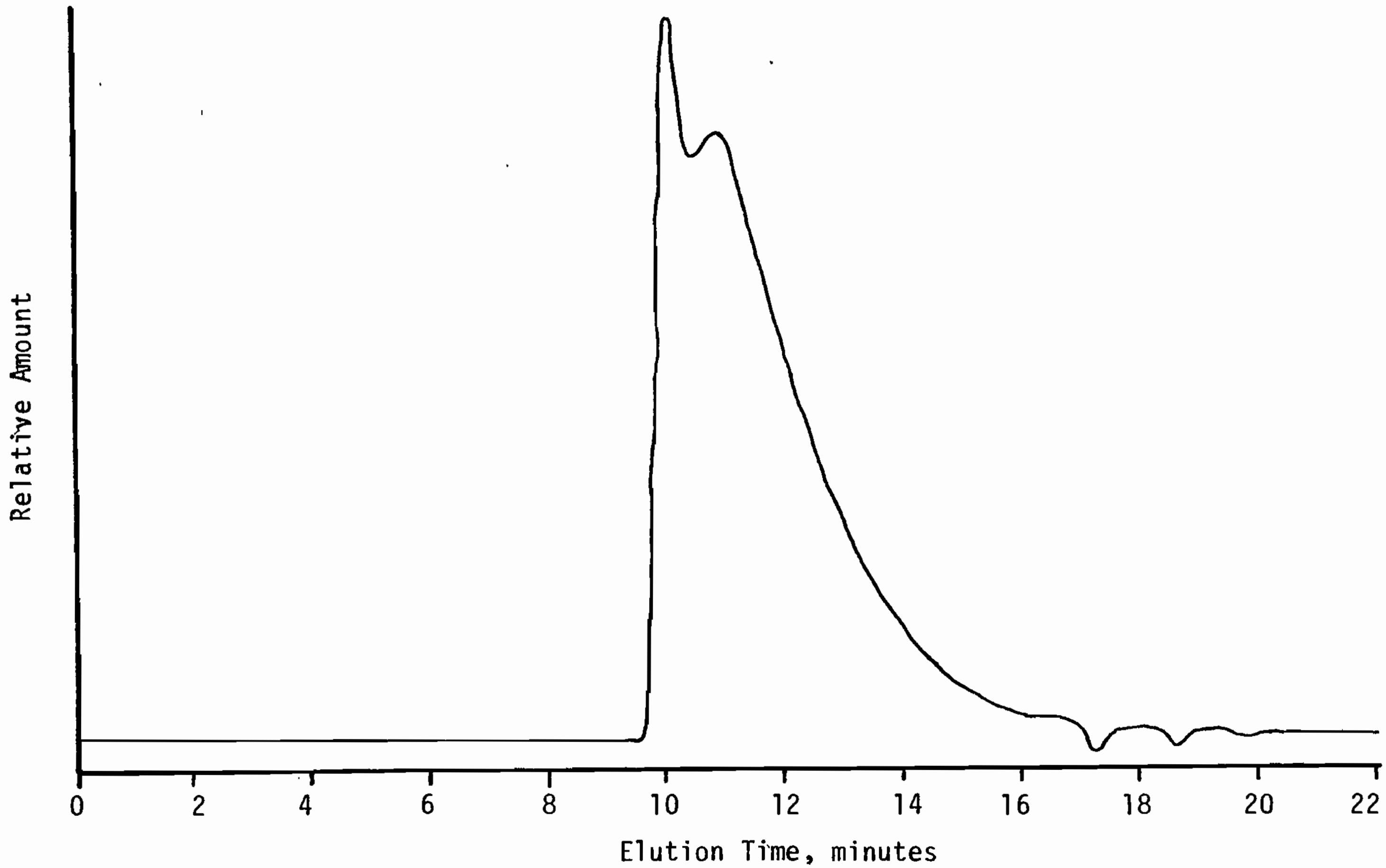

Figure D11. Chromatogram of Asphalt A, AC-10, Virgin Asphalt Cement from Dickens.

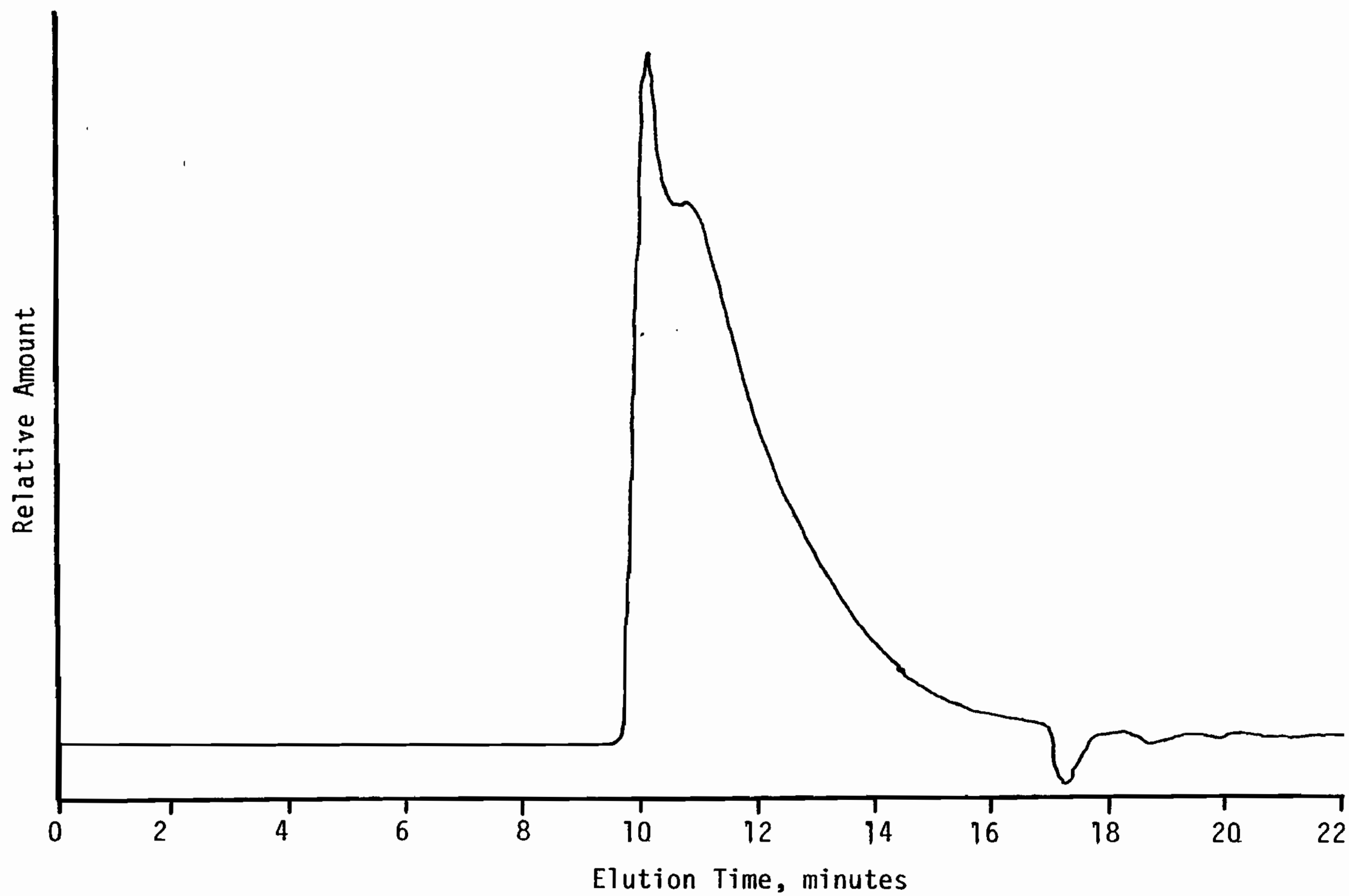

Figure D12. Chromatogram of Asphalt A, AC-20, Virgin Asphalt Cement from Dickens.

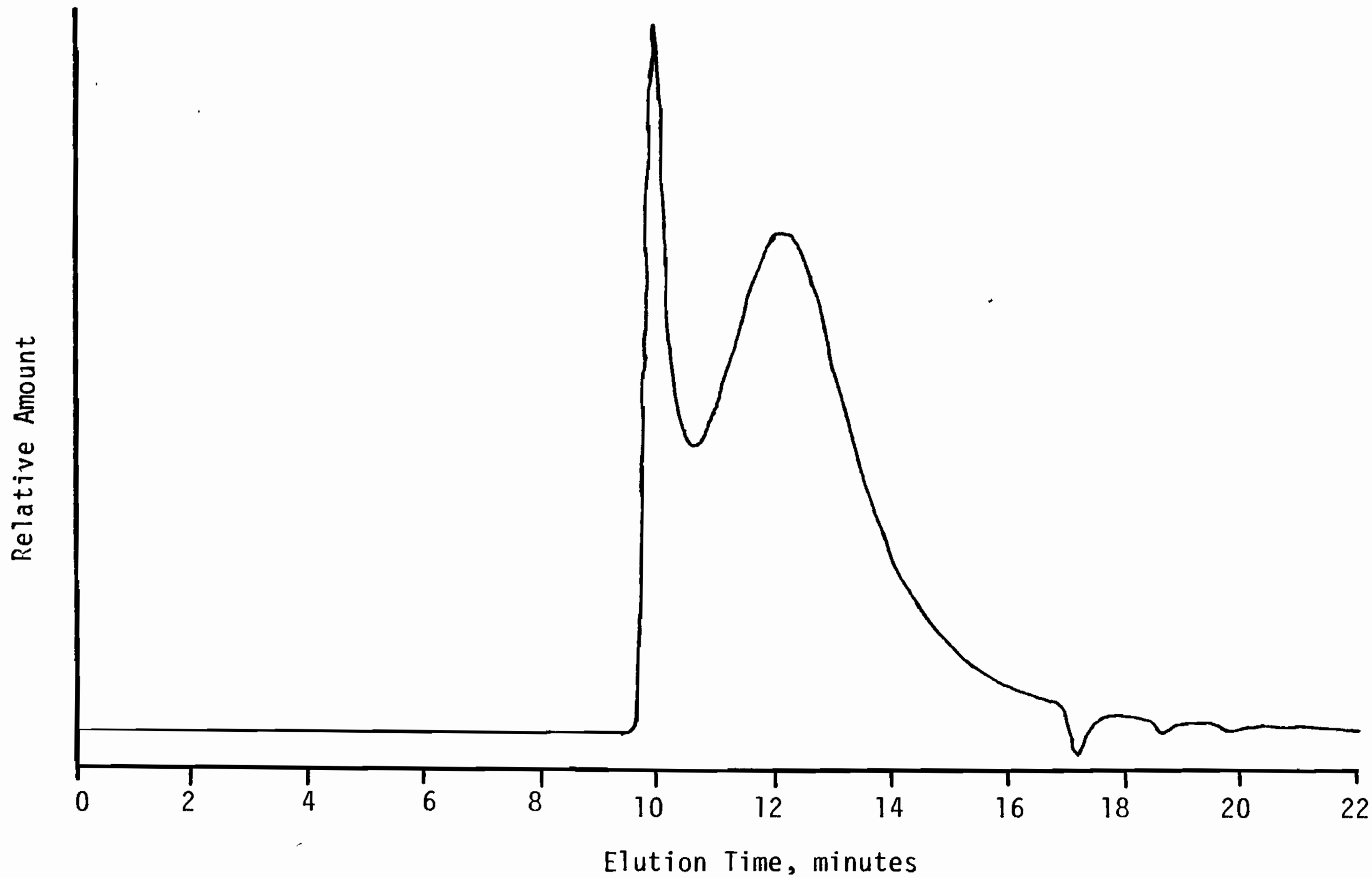

Figure D13. Chromatogram of Asphalt B, AC-20, Virgin Asphalt Cement from Dickens.

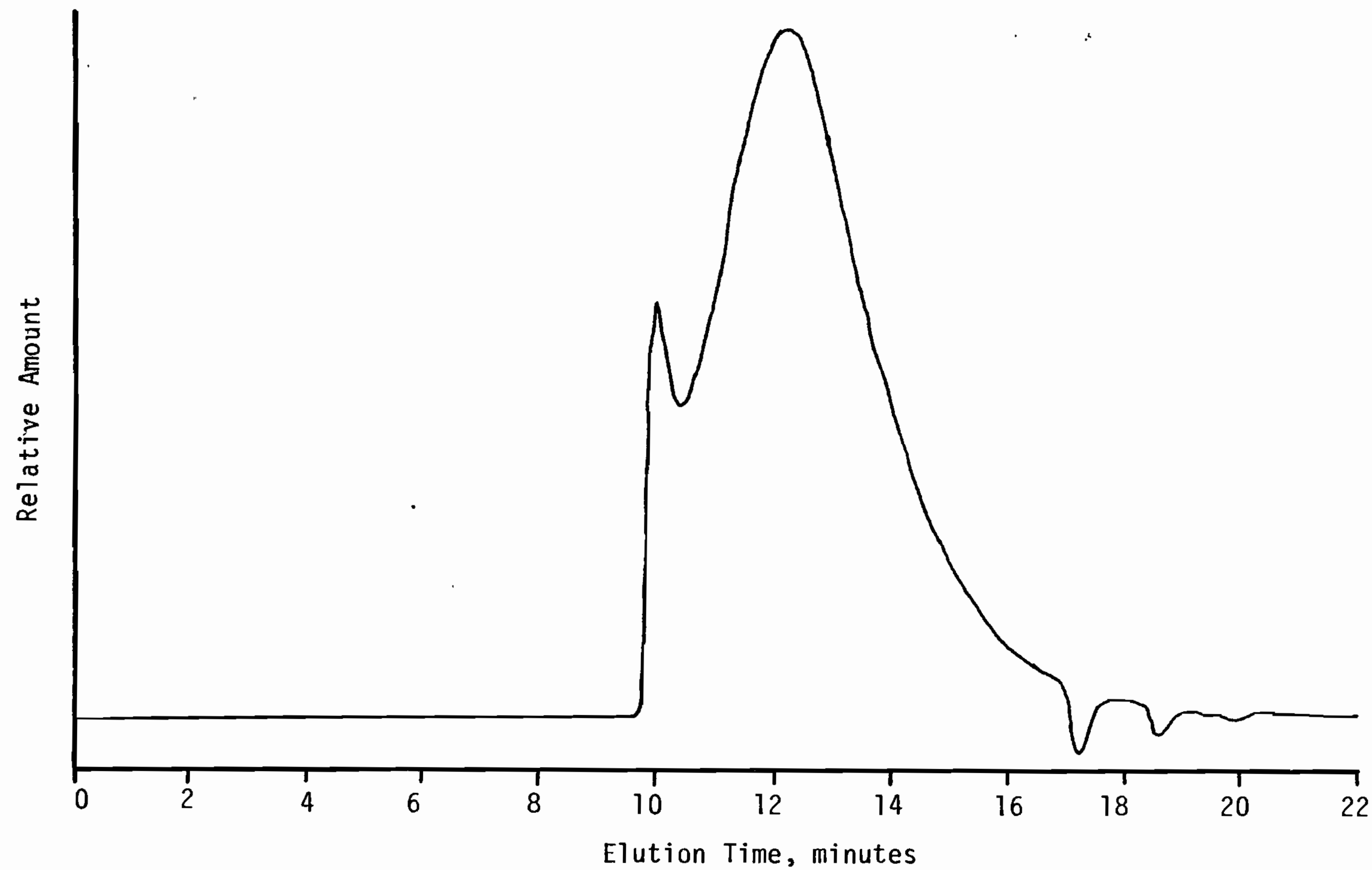

Figure B14. Chromatogram of Asphalt C, AC-20, Virgin Asphalt Cement from Dickens.

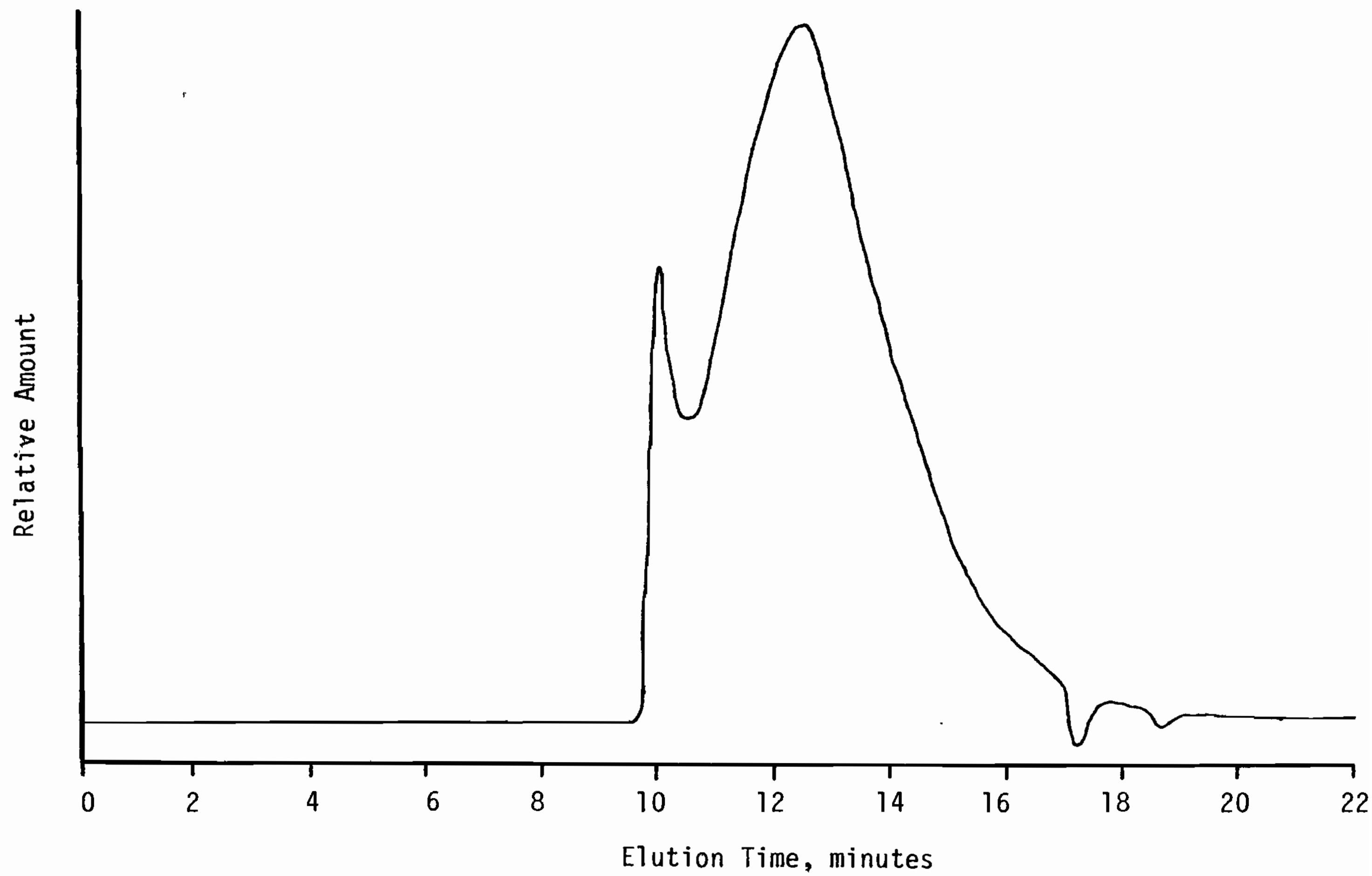

Figure D15. Chromatogram of Asphalt E, AC-10, Virgin Asphalt Cement from Dickens.

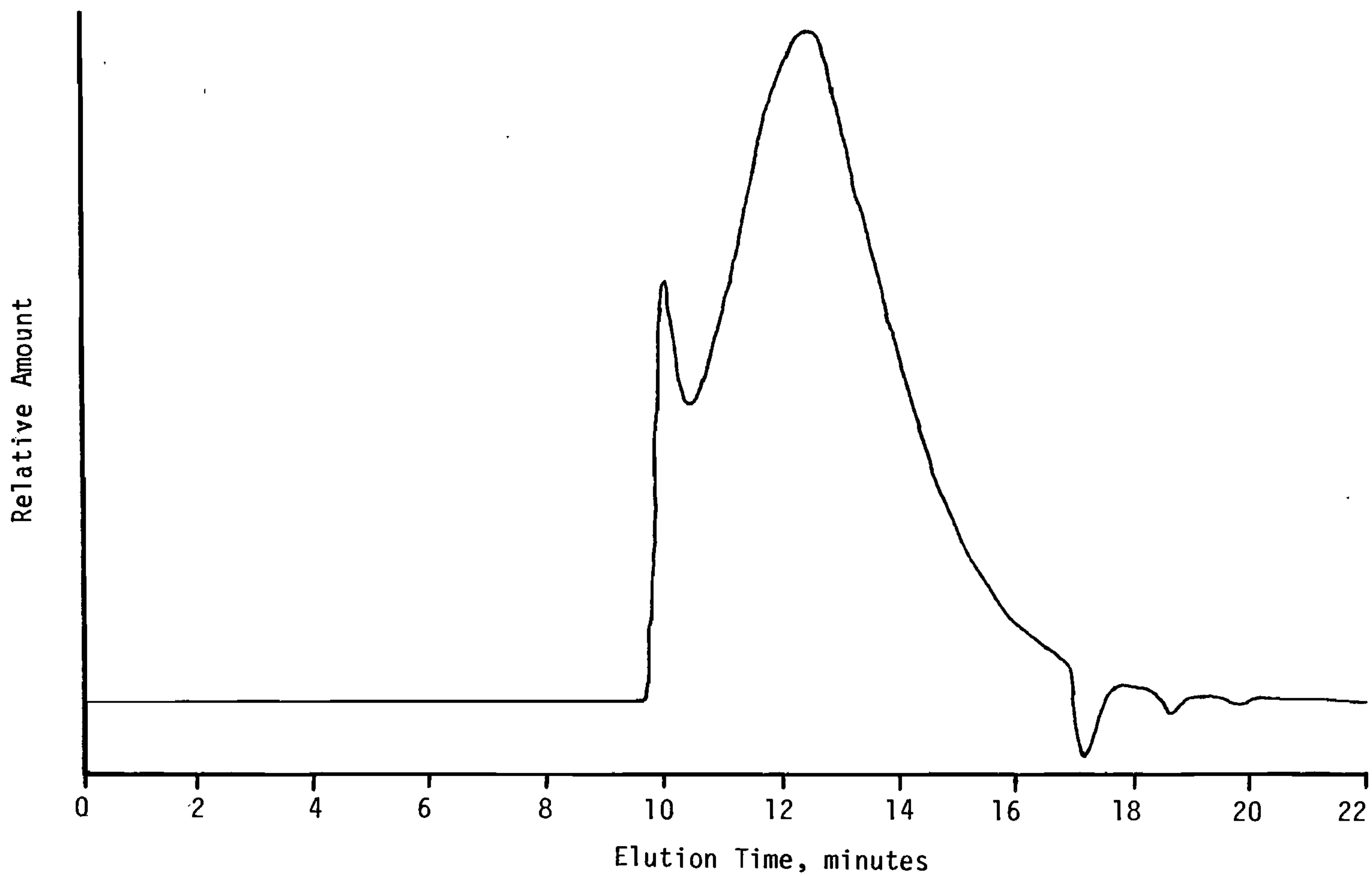

Figure D16. Chromatogram of Asphalt E, AC-20, Virgin Asphalt Cement from Dickens.

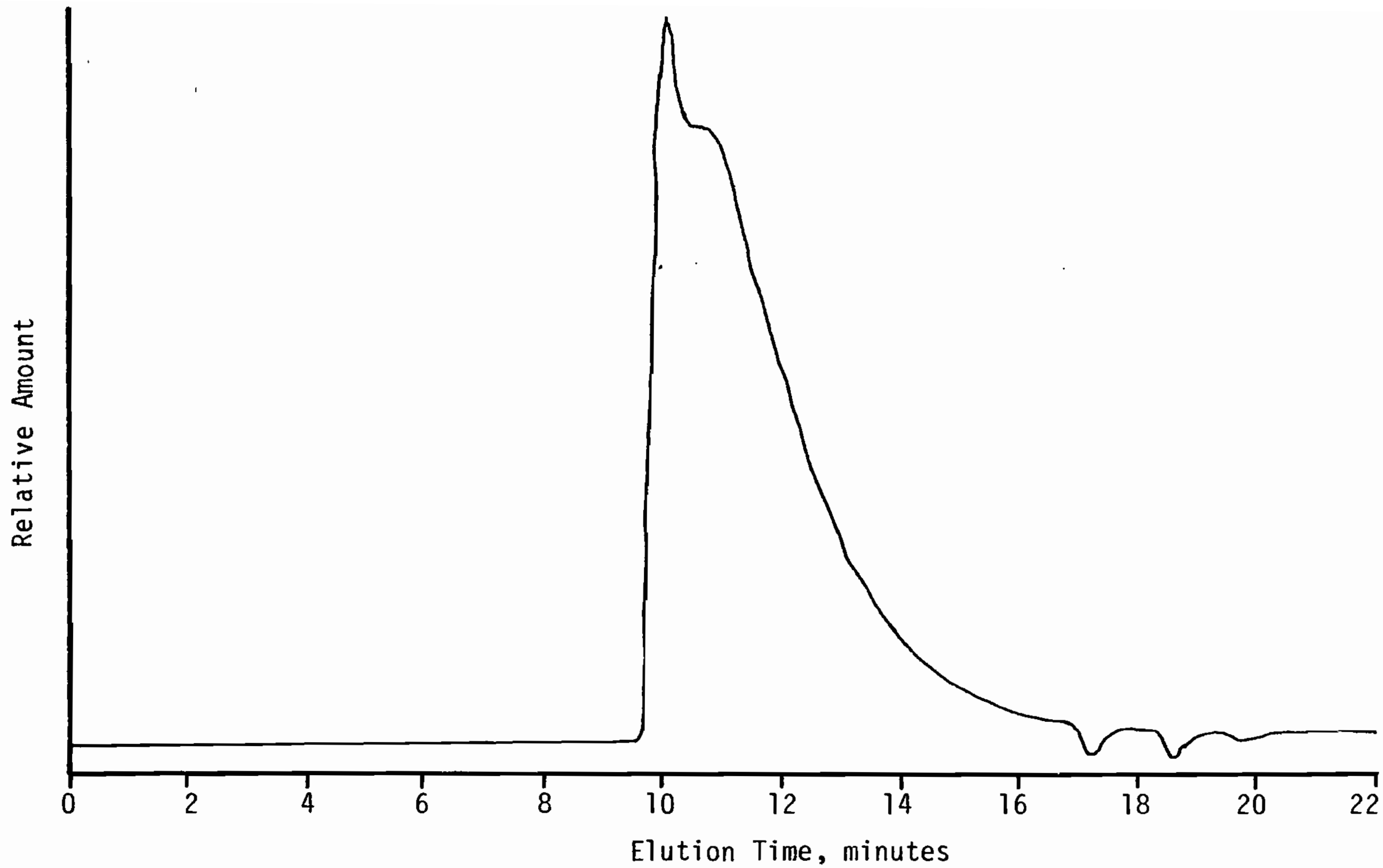

Figure D17. Chromatogram of Asphalt A, AC-10, Virgin Asphalt Cement from Dumas.

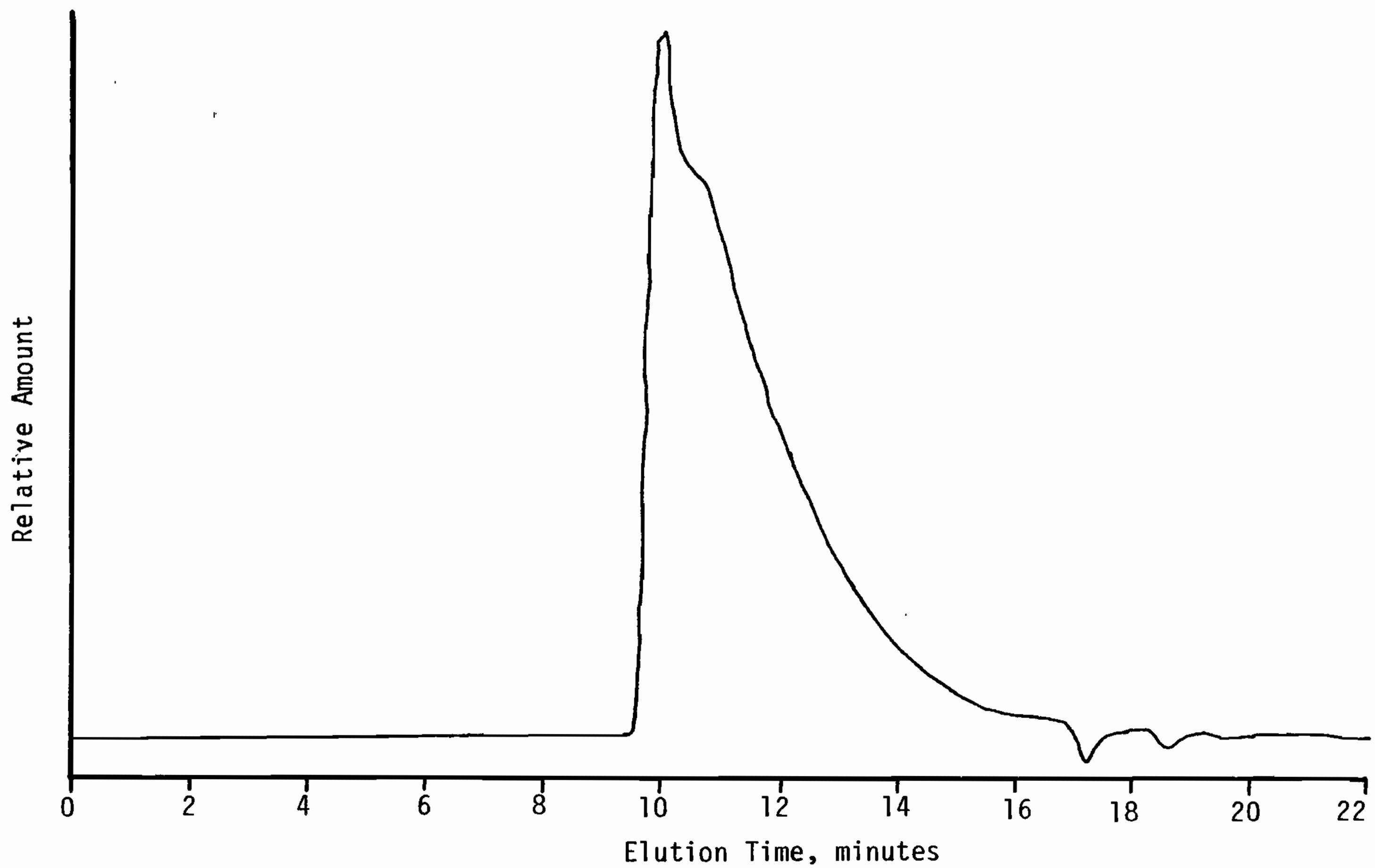

Figure D18. Chromatogram of Asphalt A, AC-20, Virgin Asphalt Cement from Dumas.

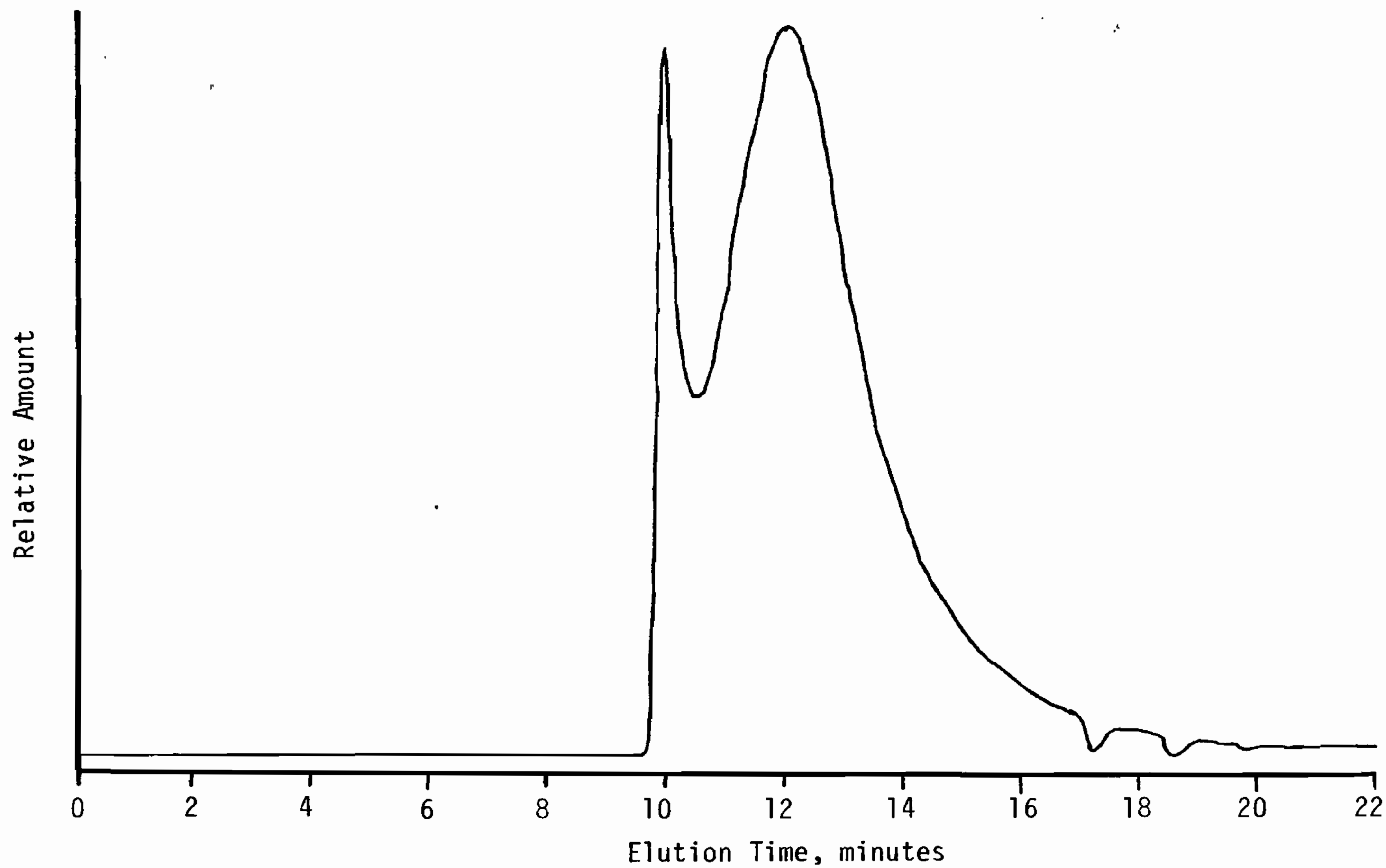

Figure D19. Chromatogram of Asphalt B, AC-10, Virgin Asphalt Cement from Dumas.

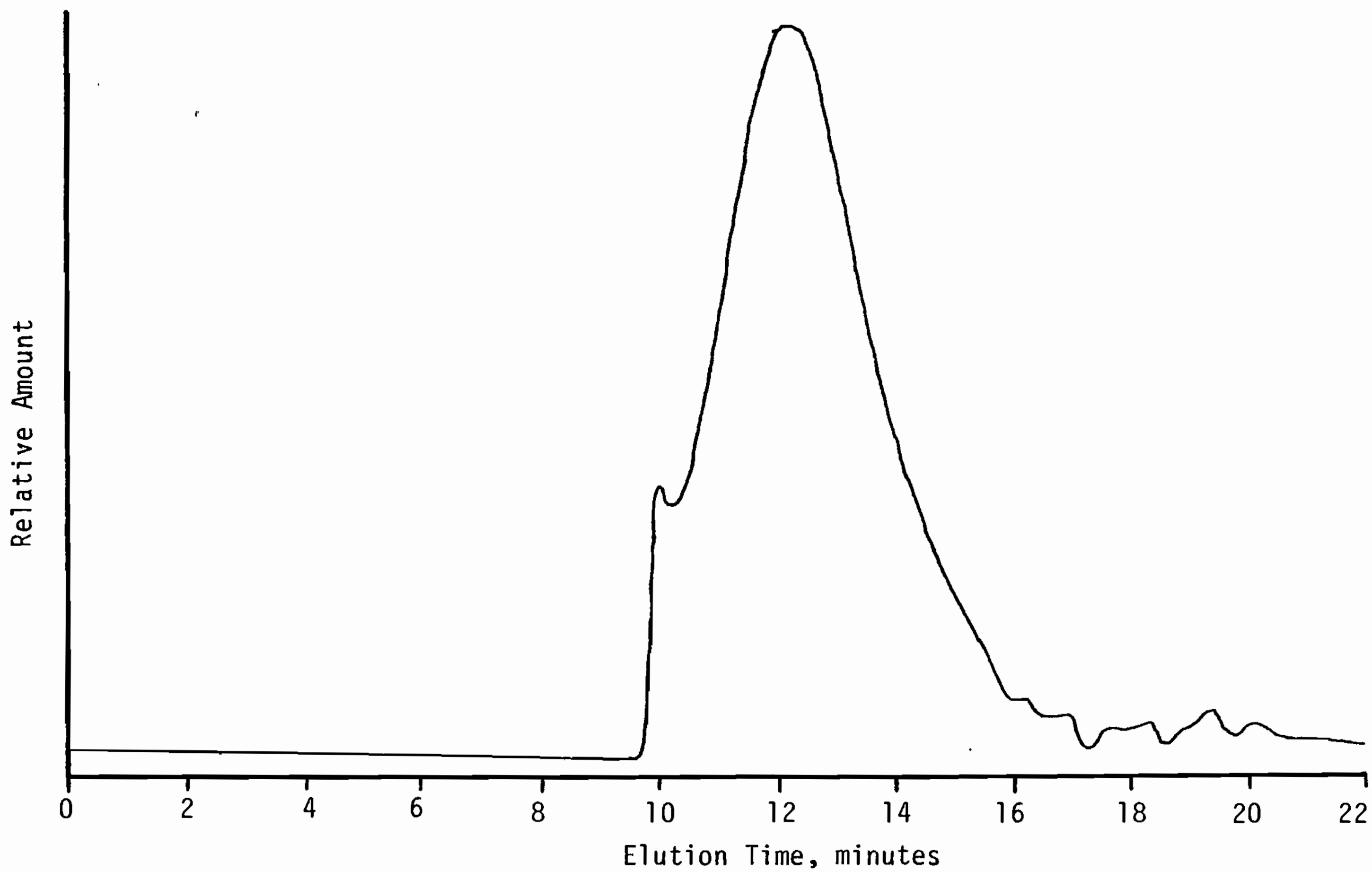

Figure D20. Chromatogram of Asphalt C, AC-10, Virgin Asphalt Cement from Dumas.

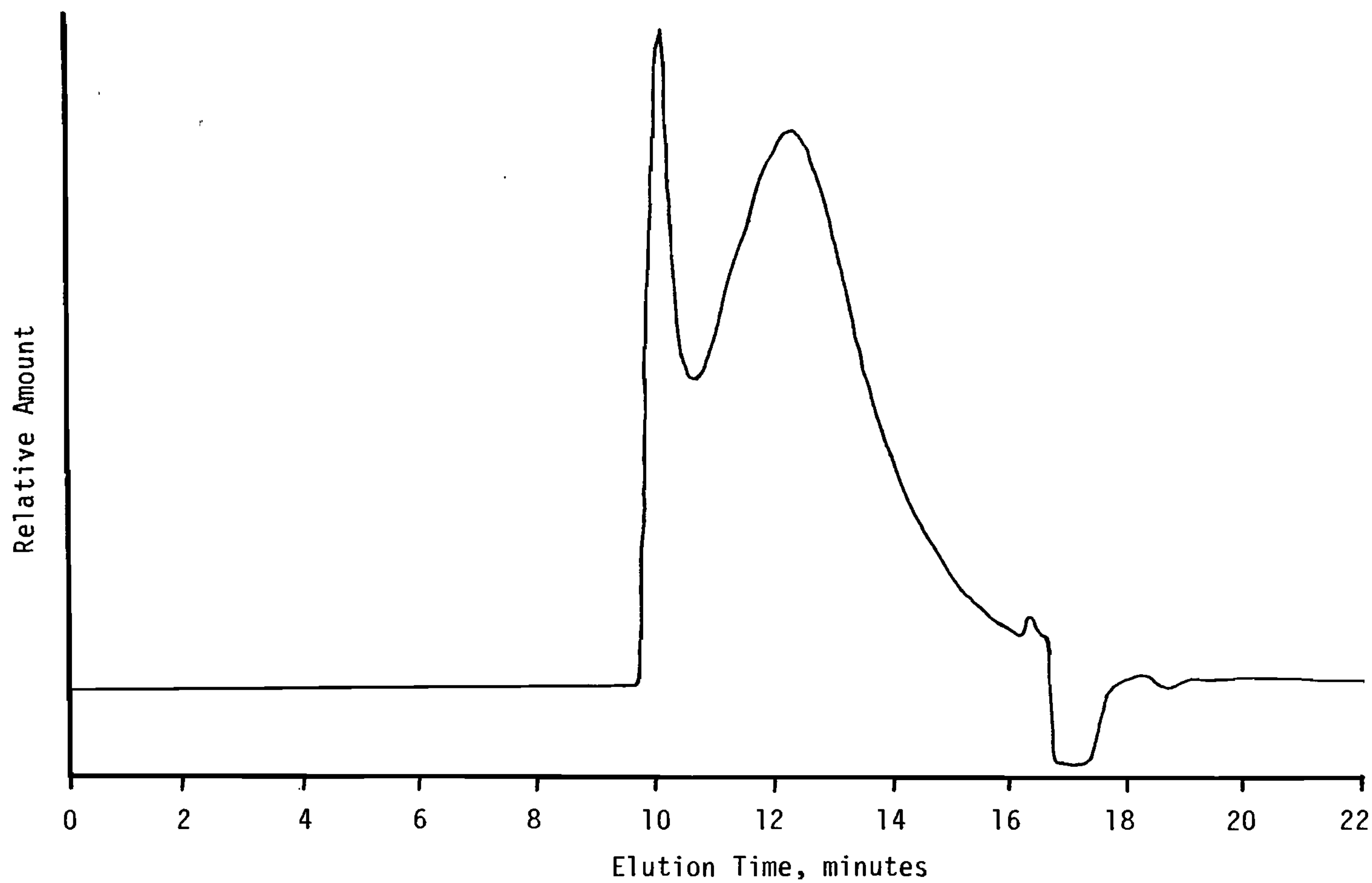

Figure D21. Chromatogram of Asphalt D, AC-10, Virgin Asphalt Cement from Dumas.

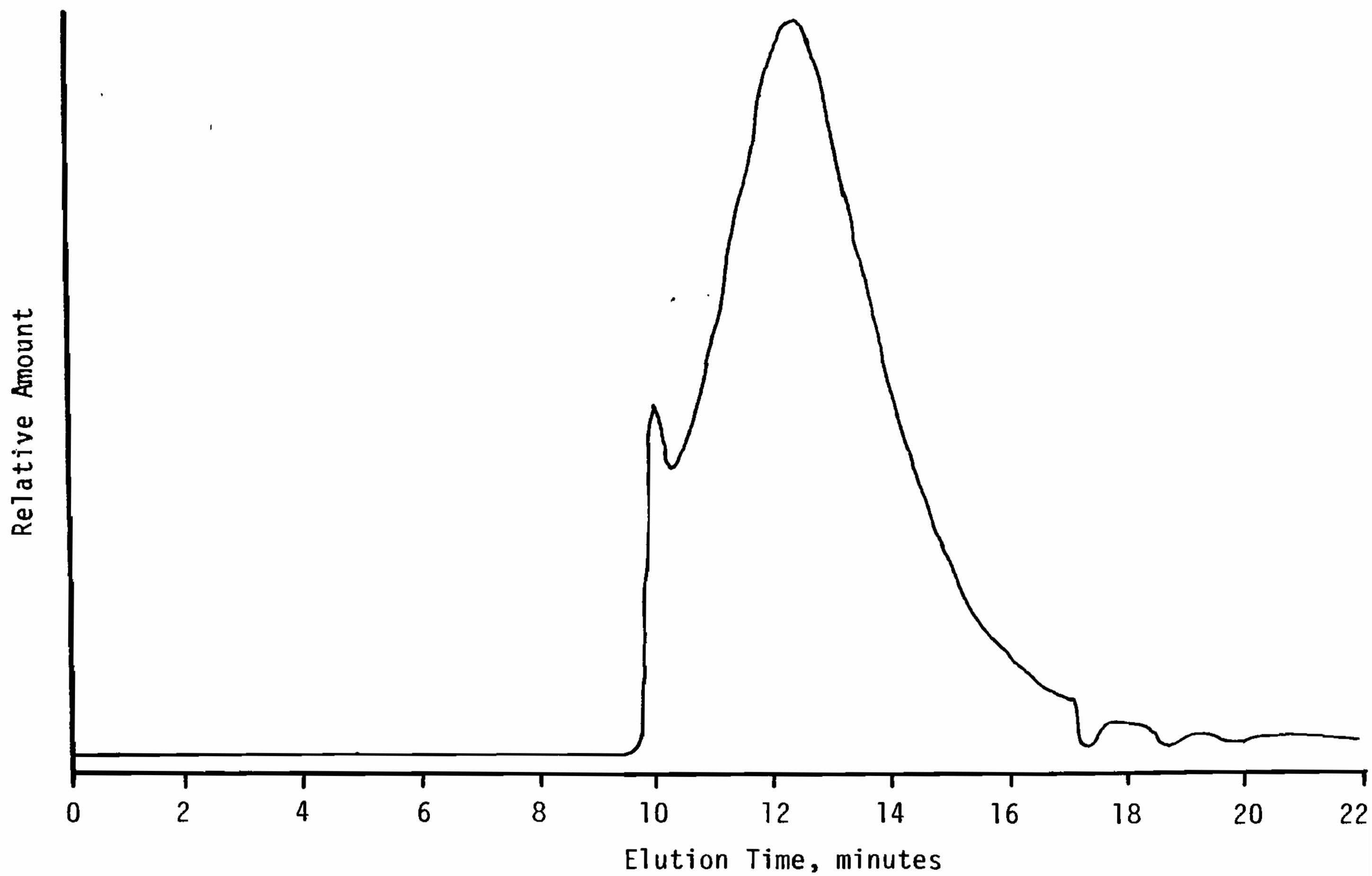

Figure D22. Chromatogram of Asphalt E, AC-10, Virgin Asphalt Cement from Dumas.

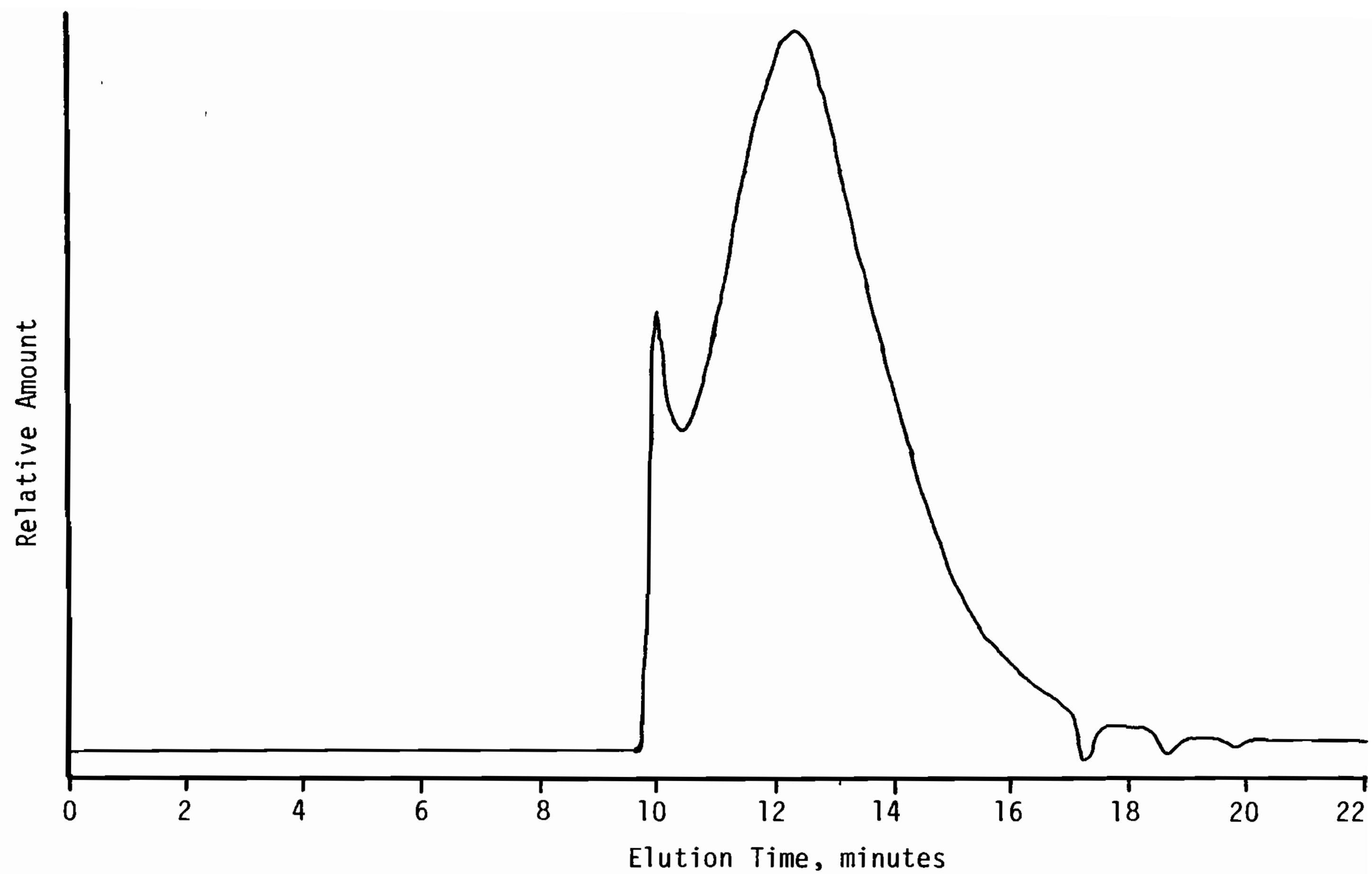

Figure D23. Chromatogram of Asphalt E, AC-20, Virgin Asphalt Cement from Dumas.

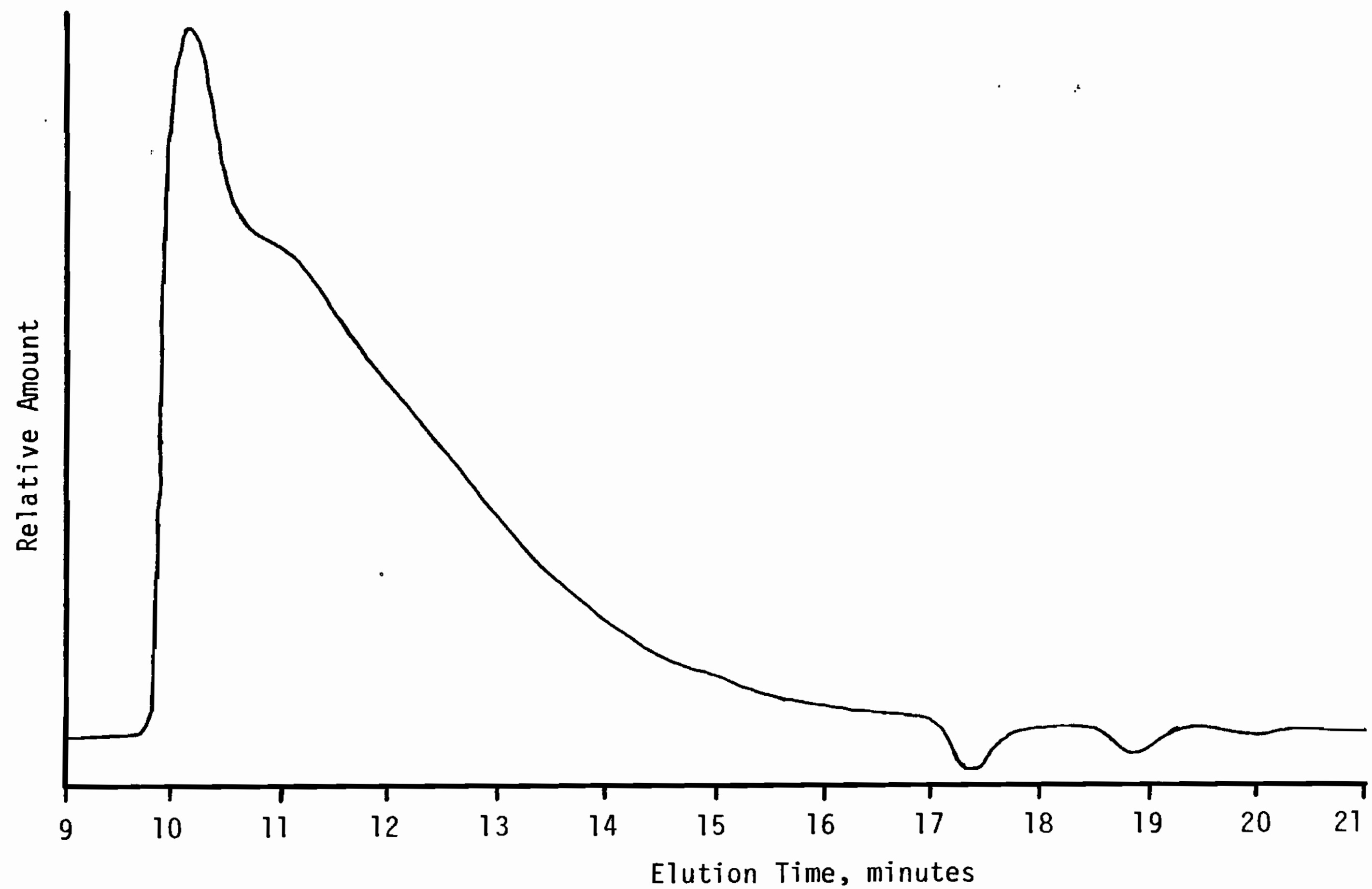

Figure D24. Chromatogram of Asphalt A, AC-10, Extracted from Dumas Lab Molded Samples.

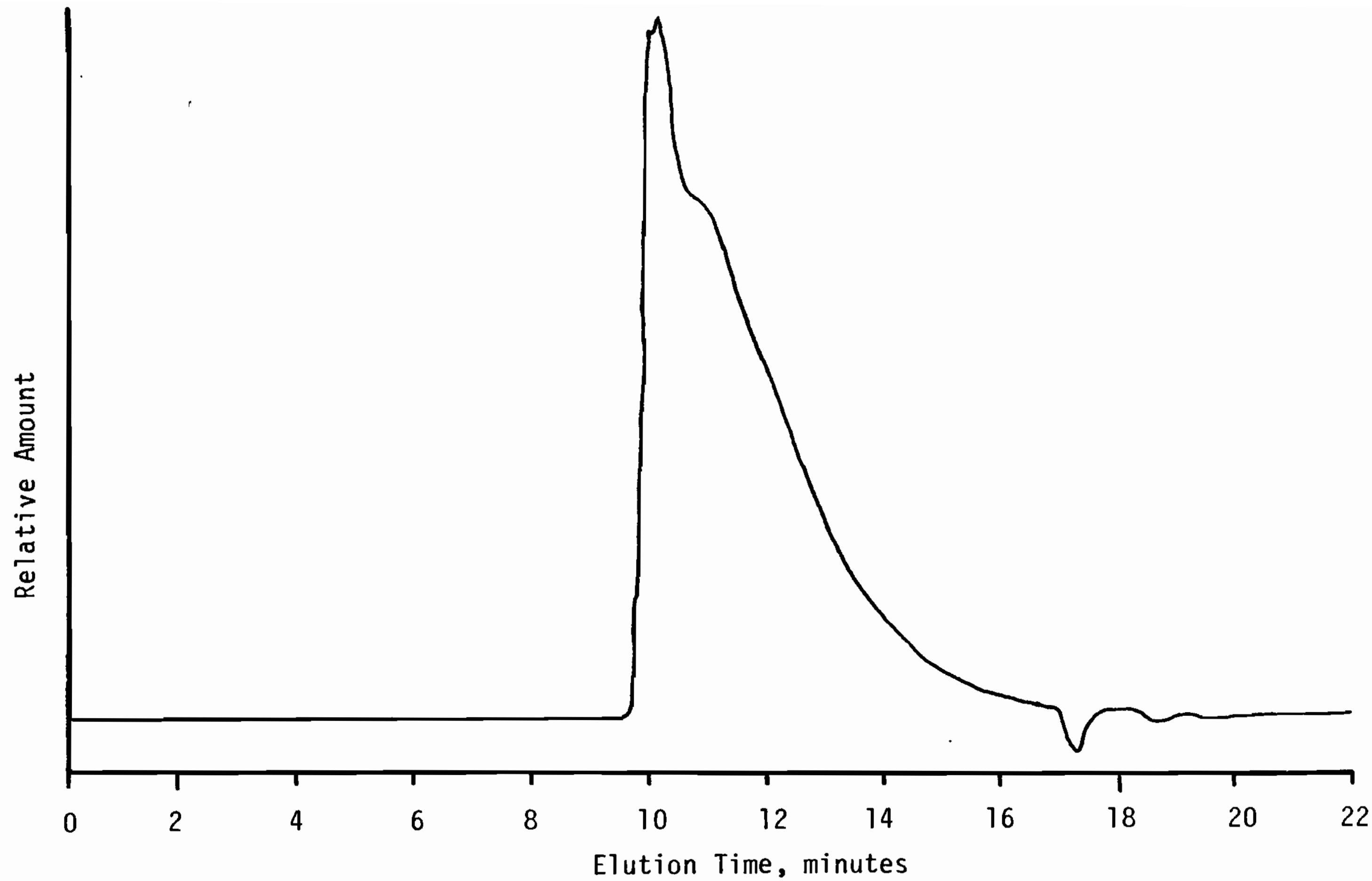

Figure D25. Chromatogram of Asphalt B, AC-10, Extracted from Dumas Field Cores.

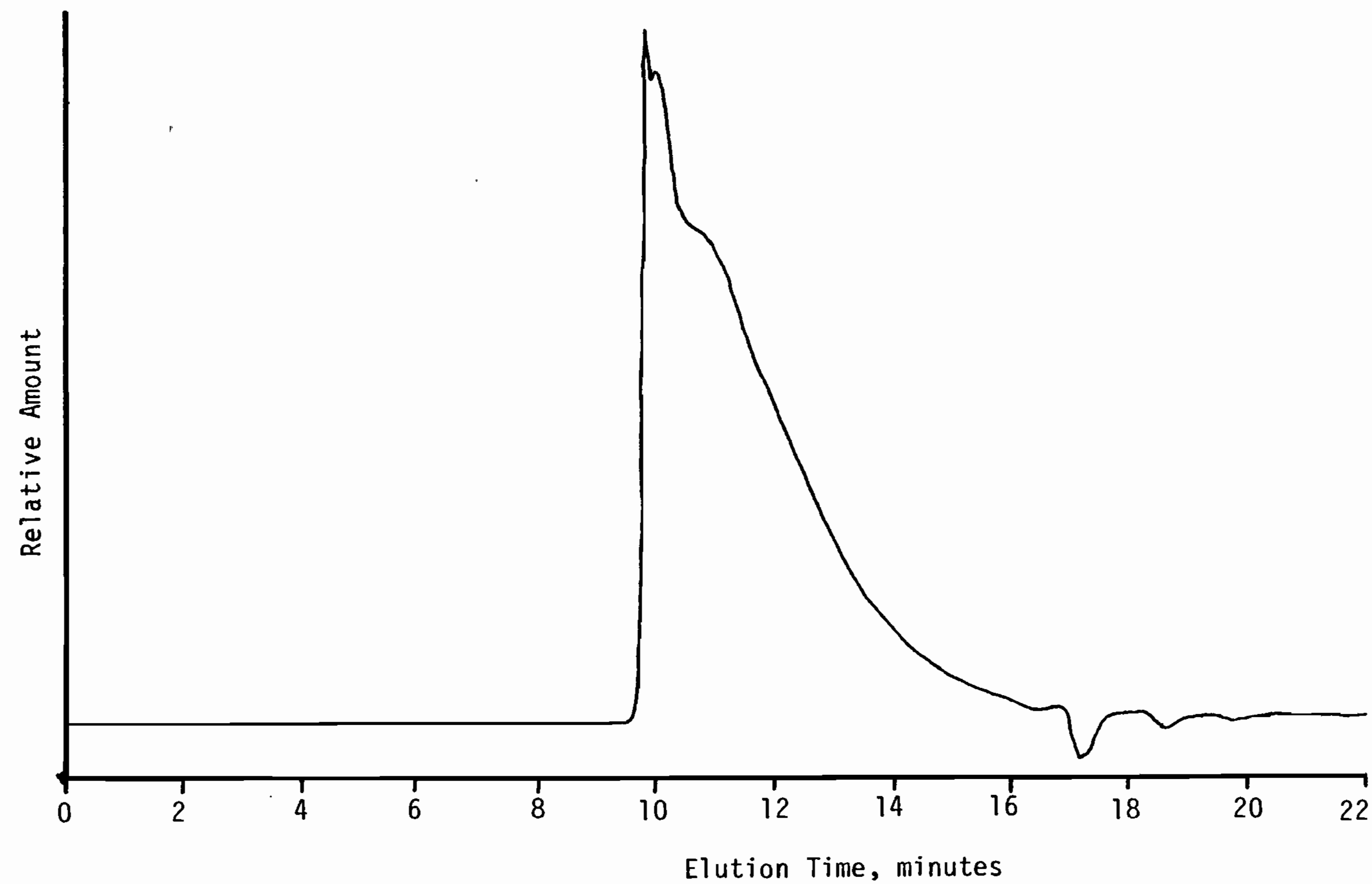

Figure D26. Chromatogram of Asphalt A, AC-10, Extracted from Dumas Field Cores.

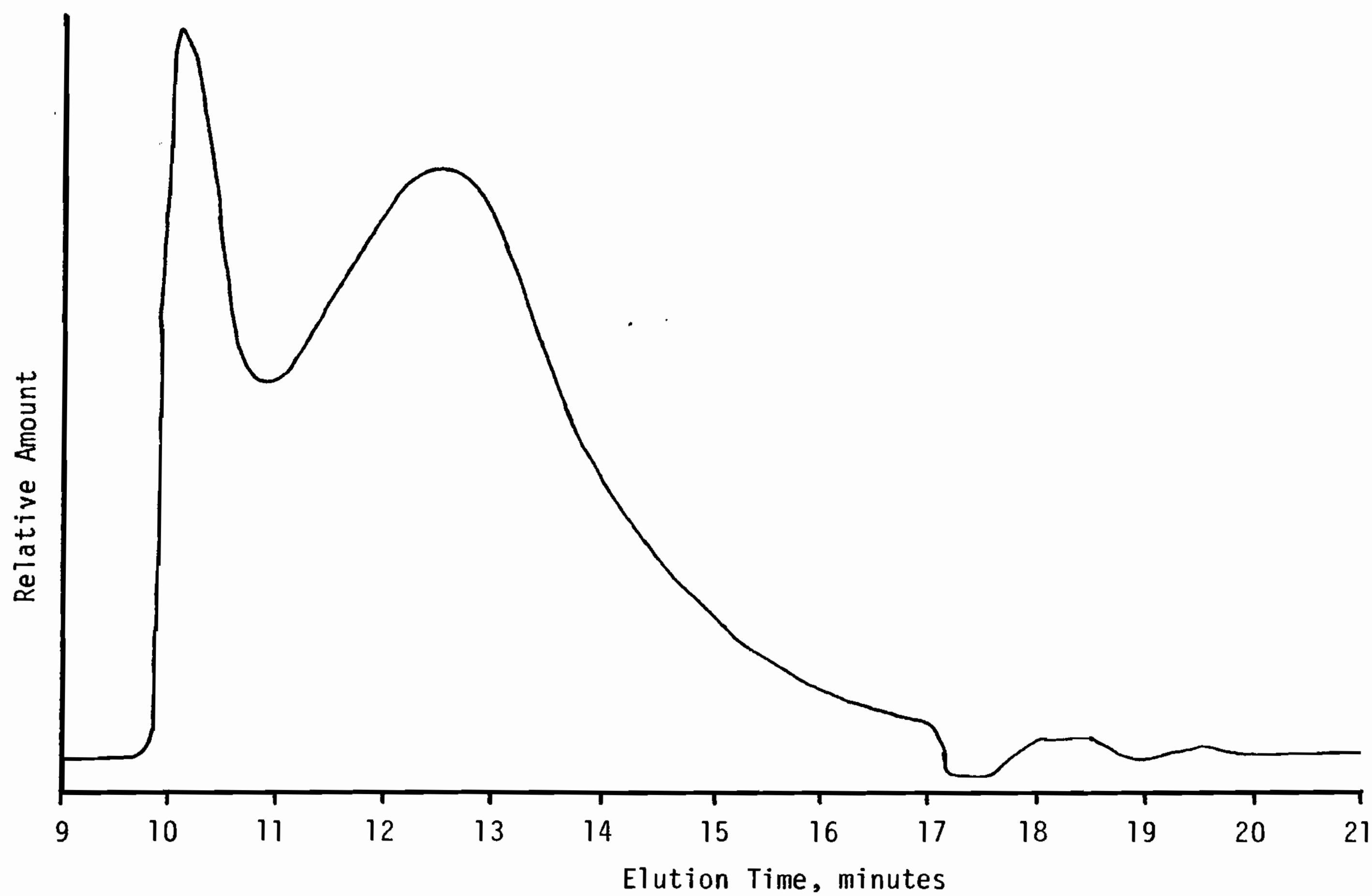

Figure D27. Chromatogram of Asphalt B, AC-10, Extracted from Dumas Lab Molded Samples.

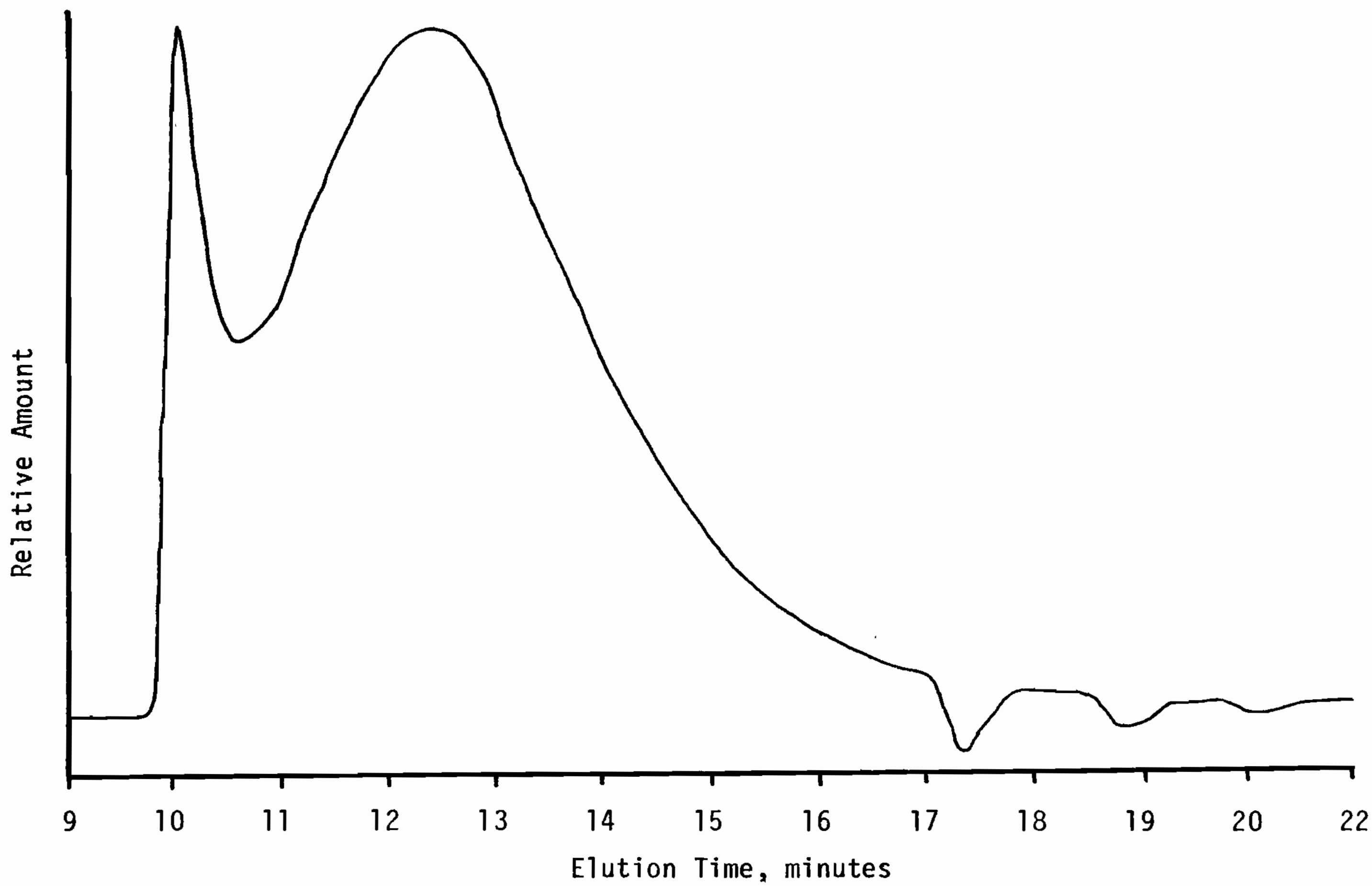

Figure D28. Chromatogram of Asphalt C, AC-10, Extracted from Dumas Lab Molded Samples.

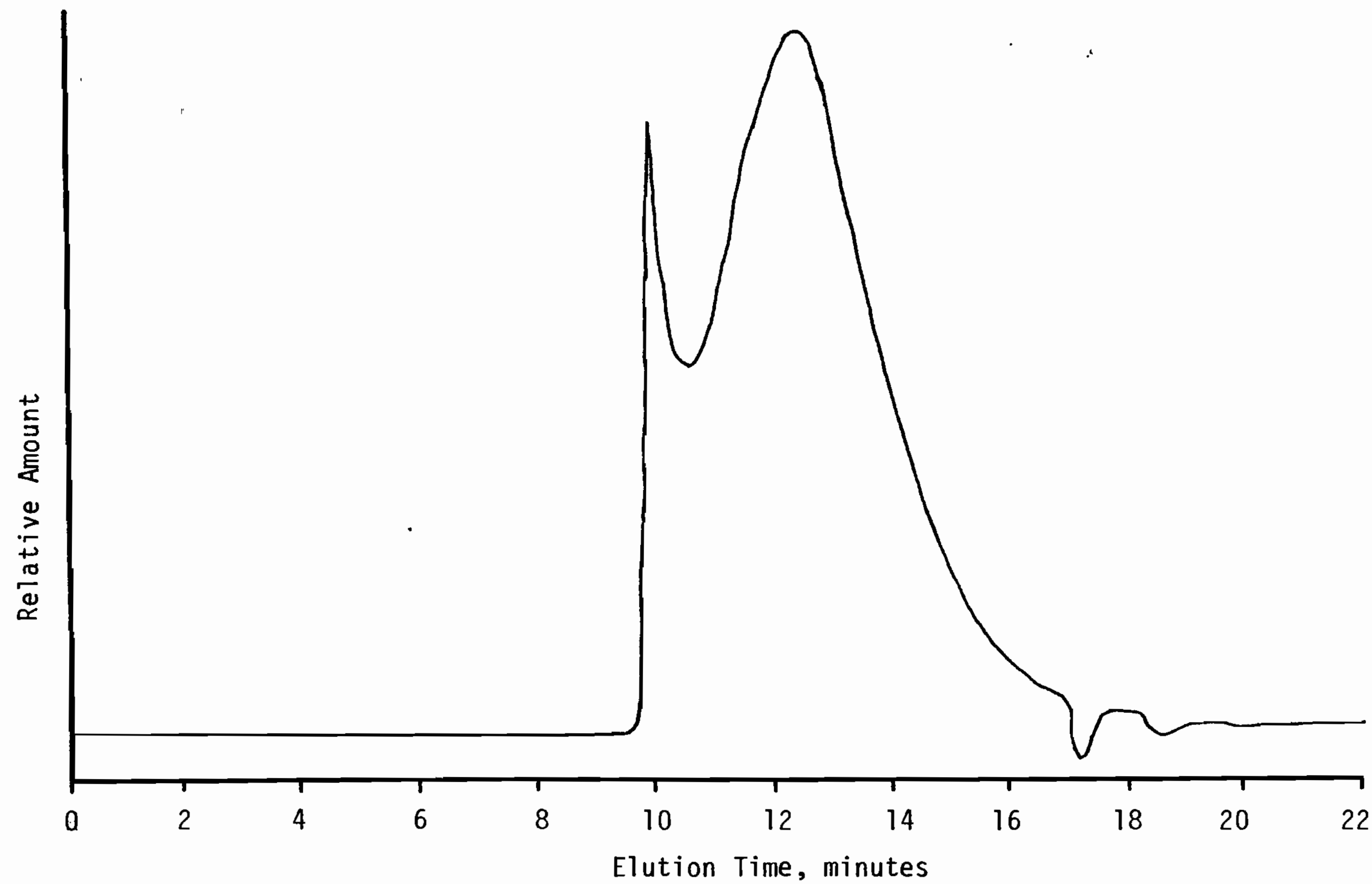

Figure D29. Chromatogram of Asphalt C, AC-10, Extracted from Dumas Field Cores.

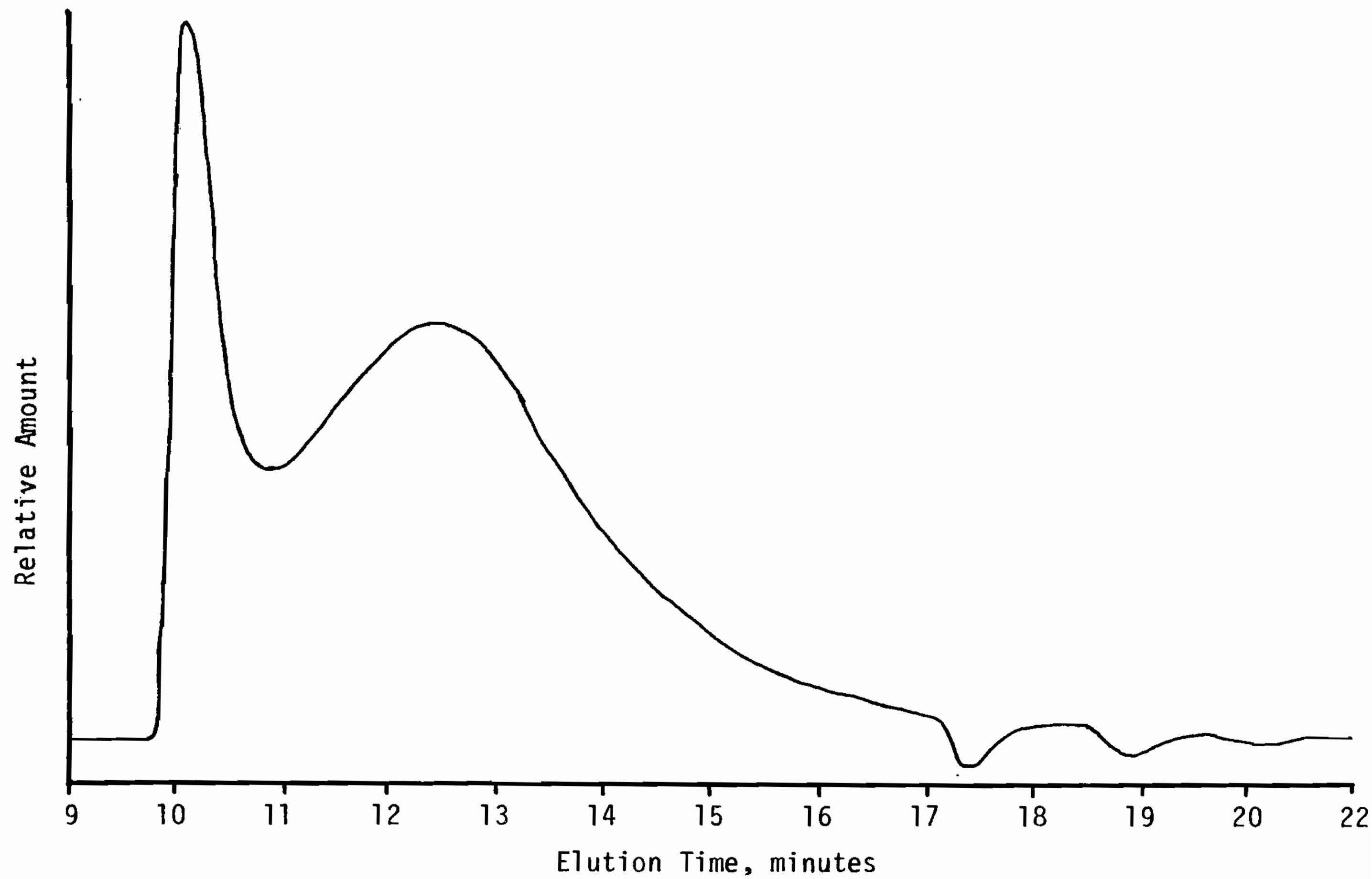

Figure B30. Chromatogram of Asphalt D, AC-10, Extracted from Dumas Lab Molded Samples.

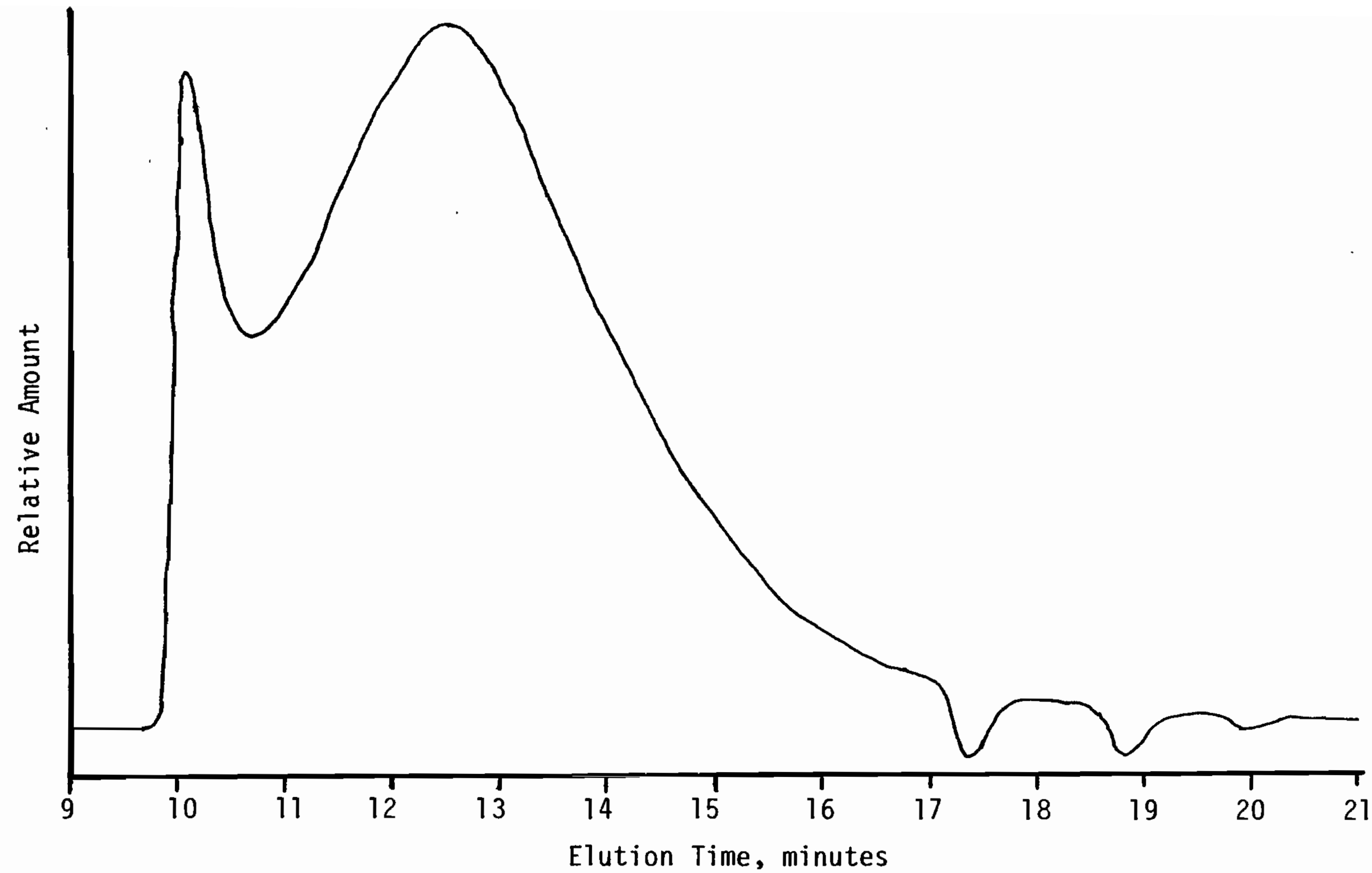

Figure D31. Chromatogram of Asphalt E, AC-10, Extracted from Dumas Lab Molded Samples.

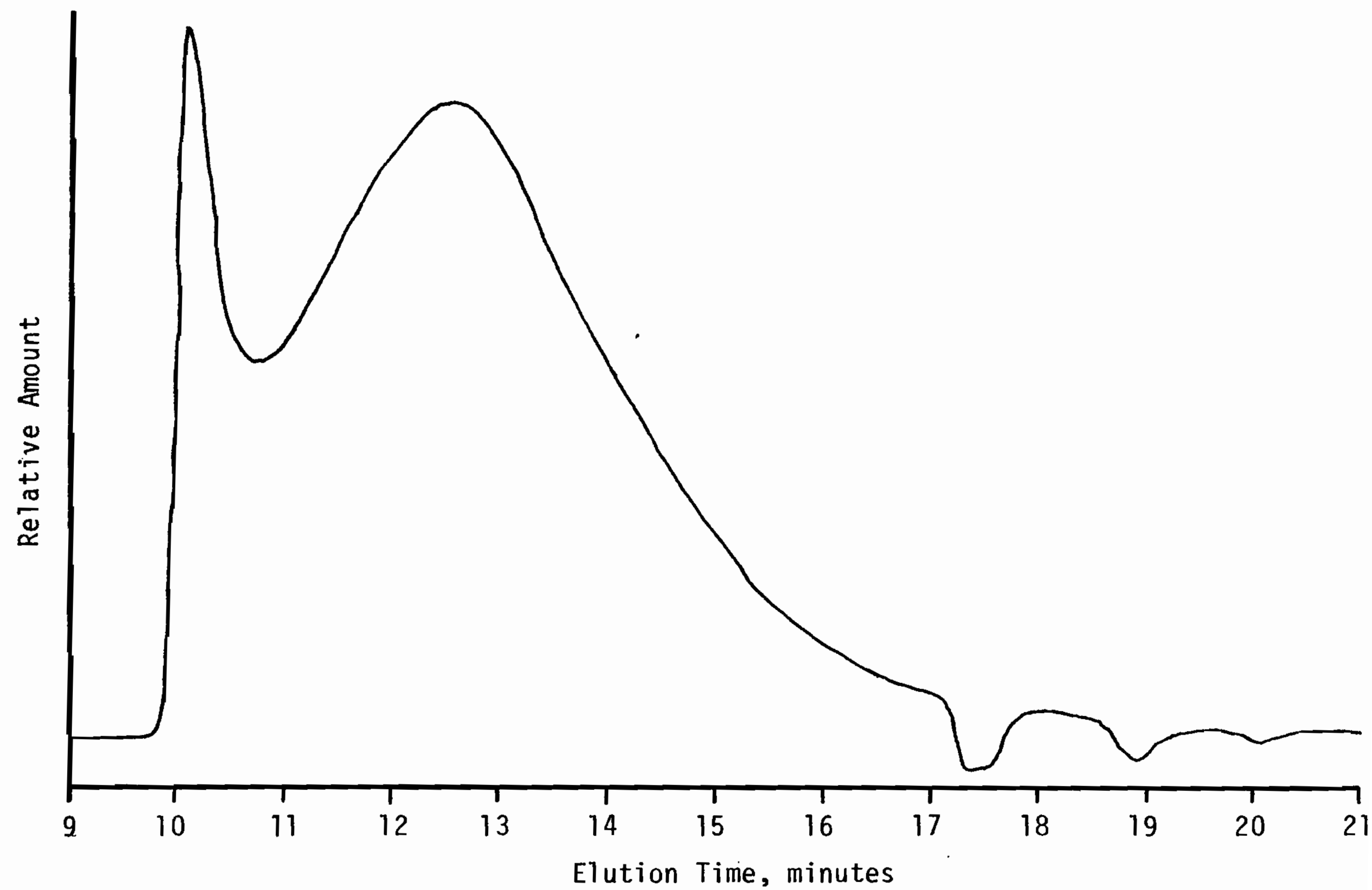

Figure D32. Chromatogram of Asphalt E, AC-20, Extracted from Dumas Lab Molded Samples.

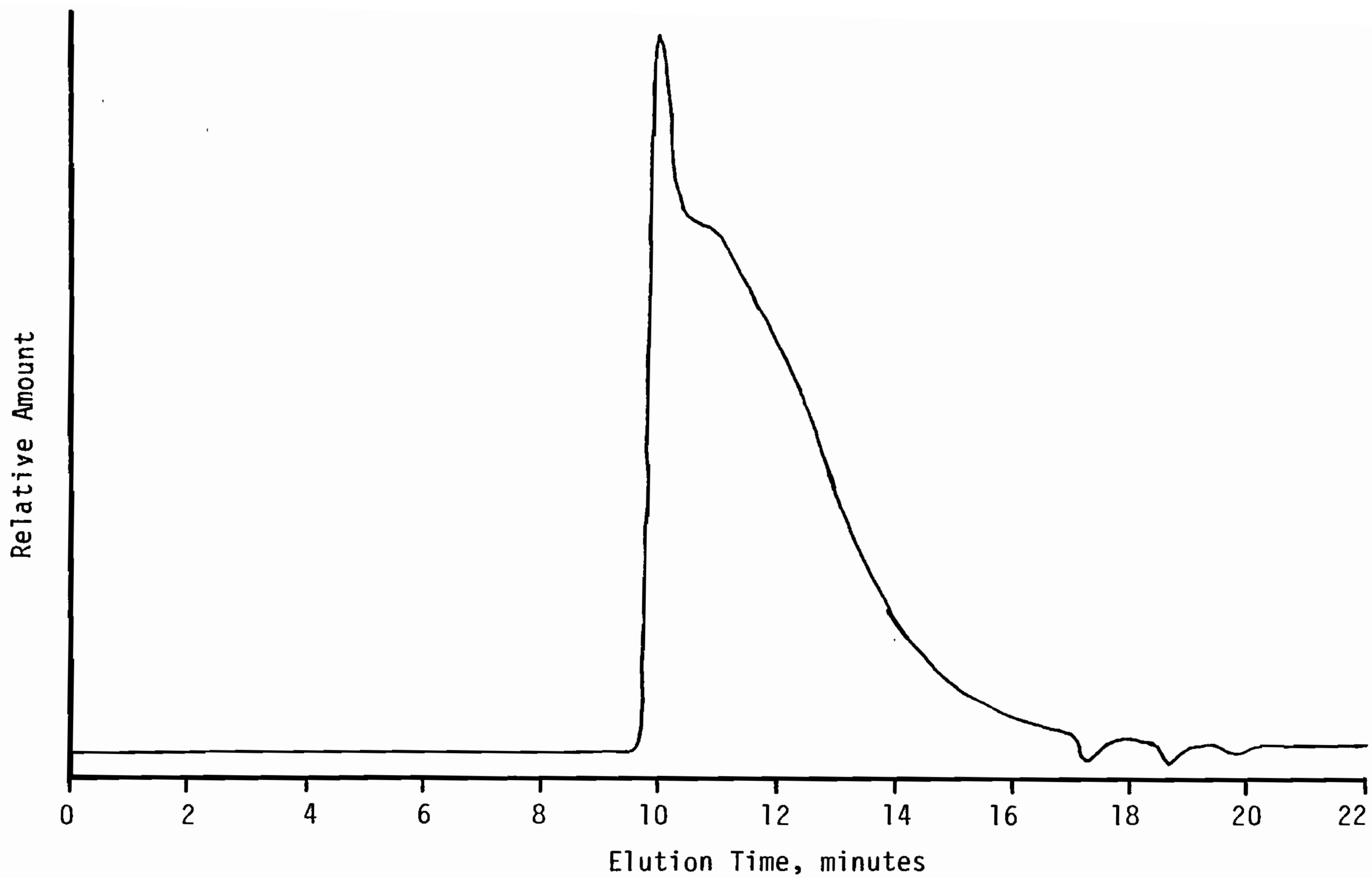

Figure D33. Chromatogram of Asphalt A, AC-20, Virgin Asphalt Cement from Lufkin.

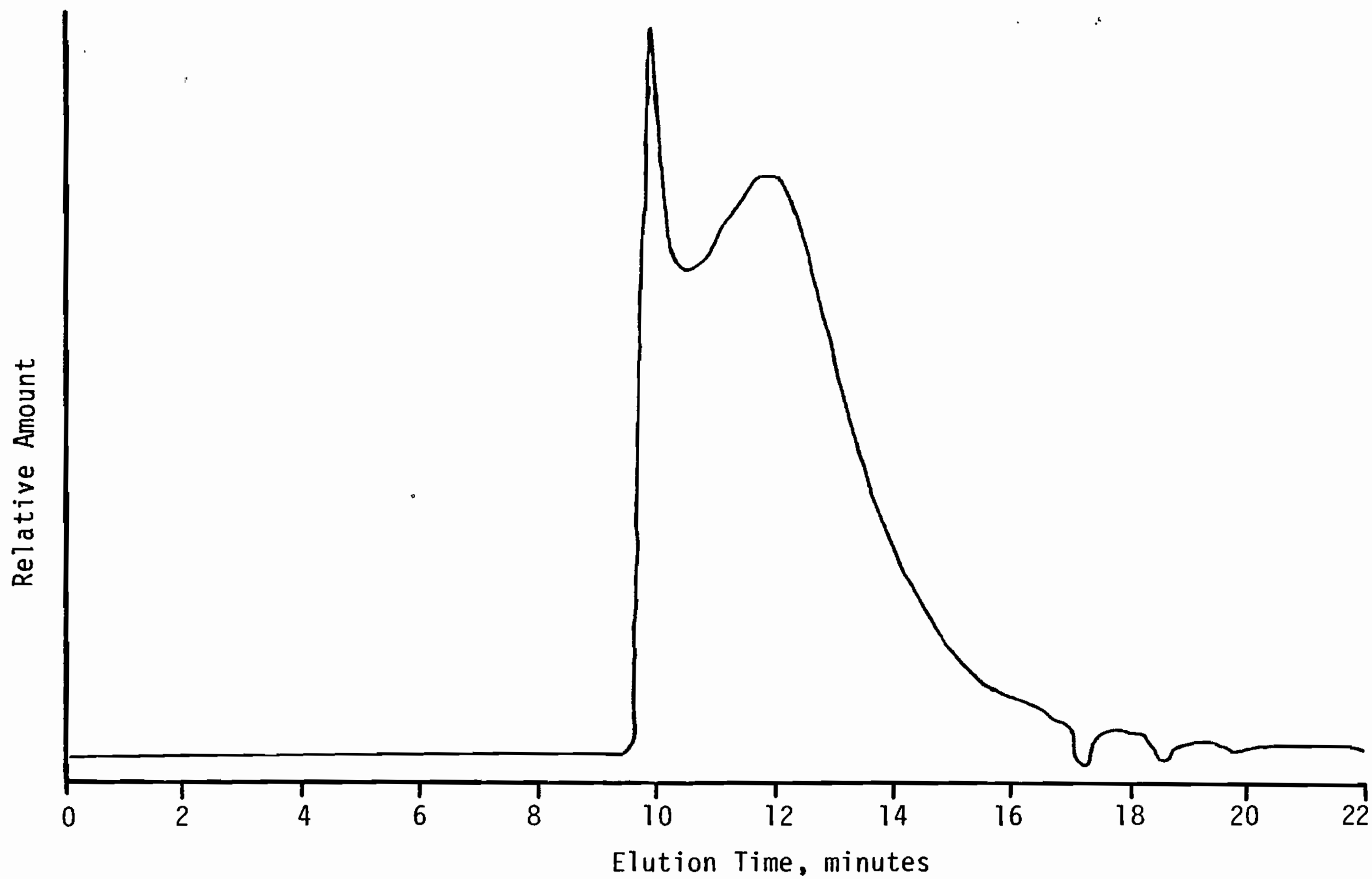

Figure D34. Chromatogram of Asphalt B, AC-20, Virgin Asphalt Cement from Lufkin.

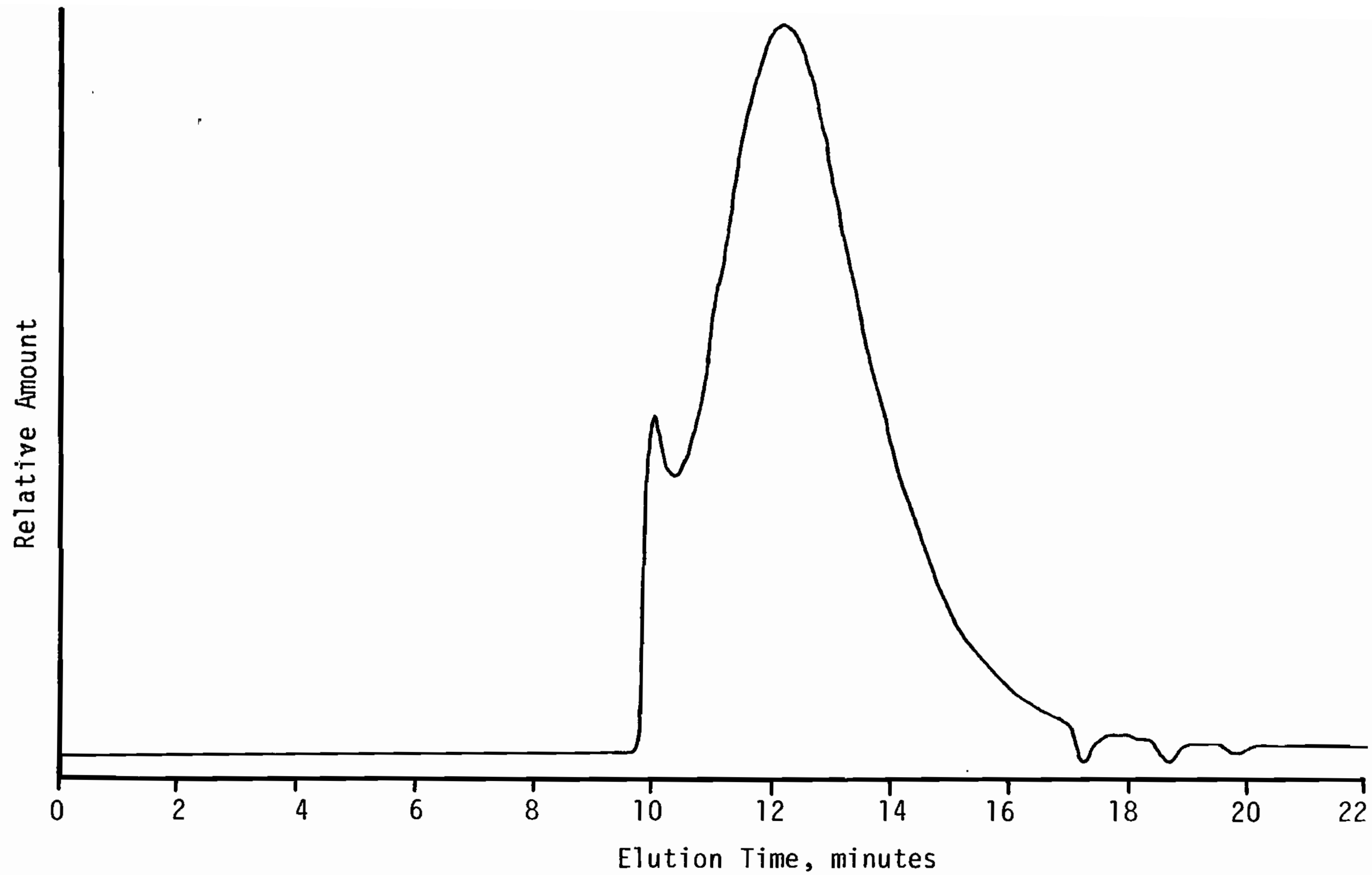

Figure D35. Chromatogram of Asphalt C, AC-20, Virgin Asphalt Cement from Lufkin.

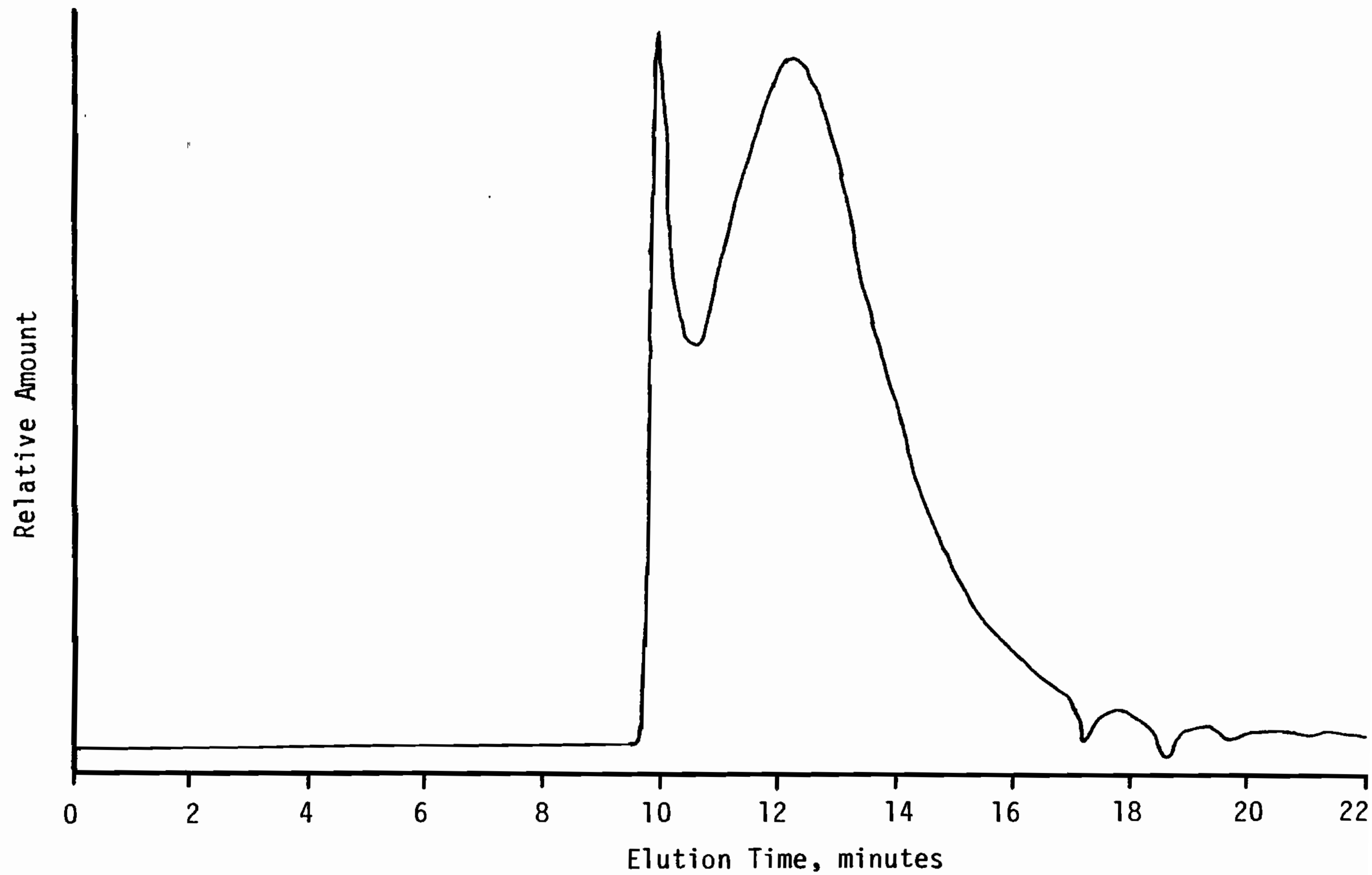

Figure B36. Chromatogram of Asphalt D, AC-10, Virgin Asphalt Cement from Lufkin.

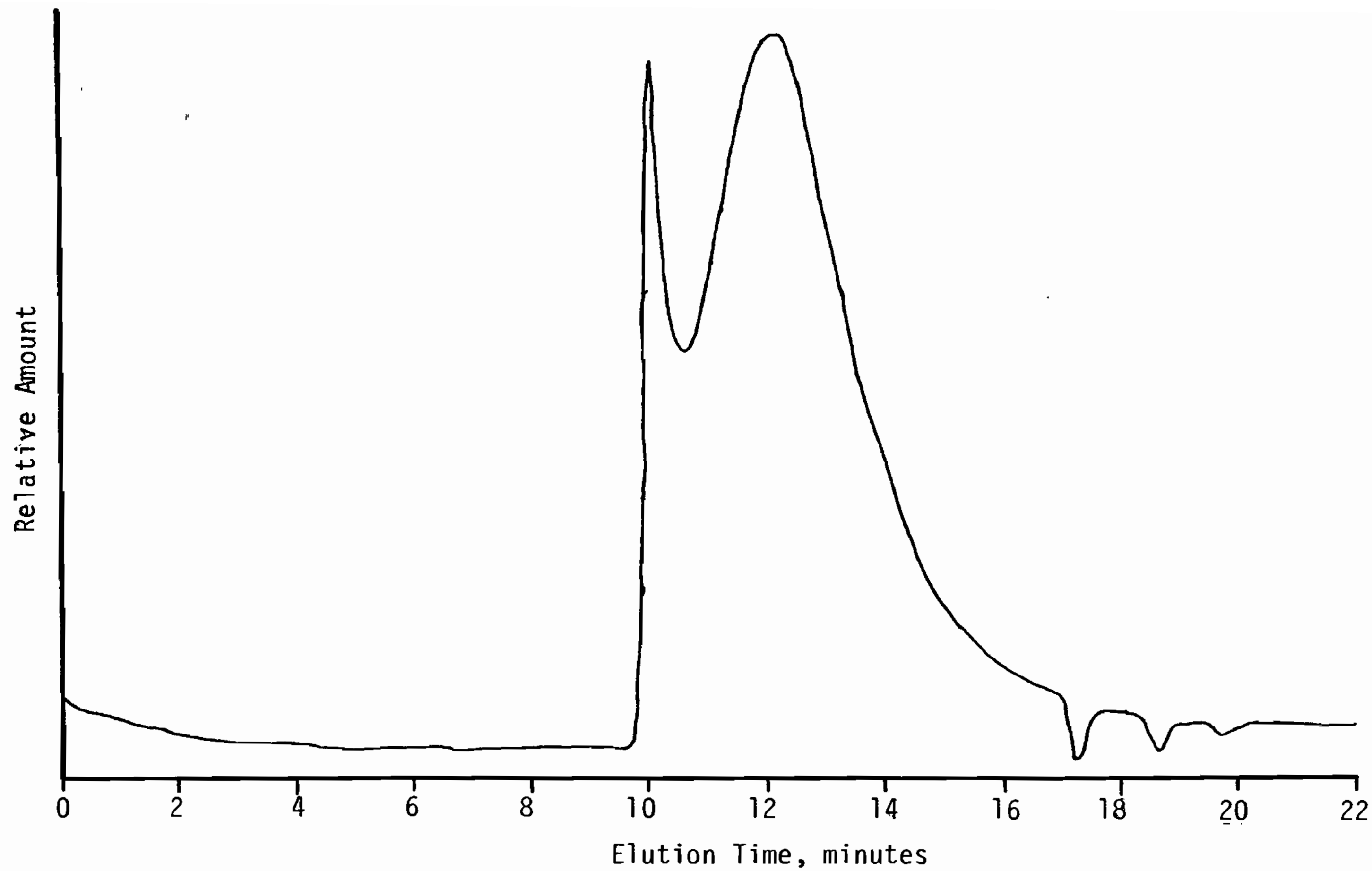

Figure D37. Chromatogram of Asphalt D, AC-20, Virgin Asphalt Cement from Lufkin.

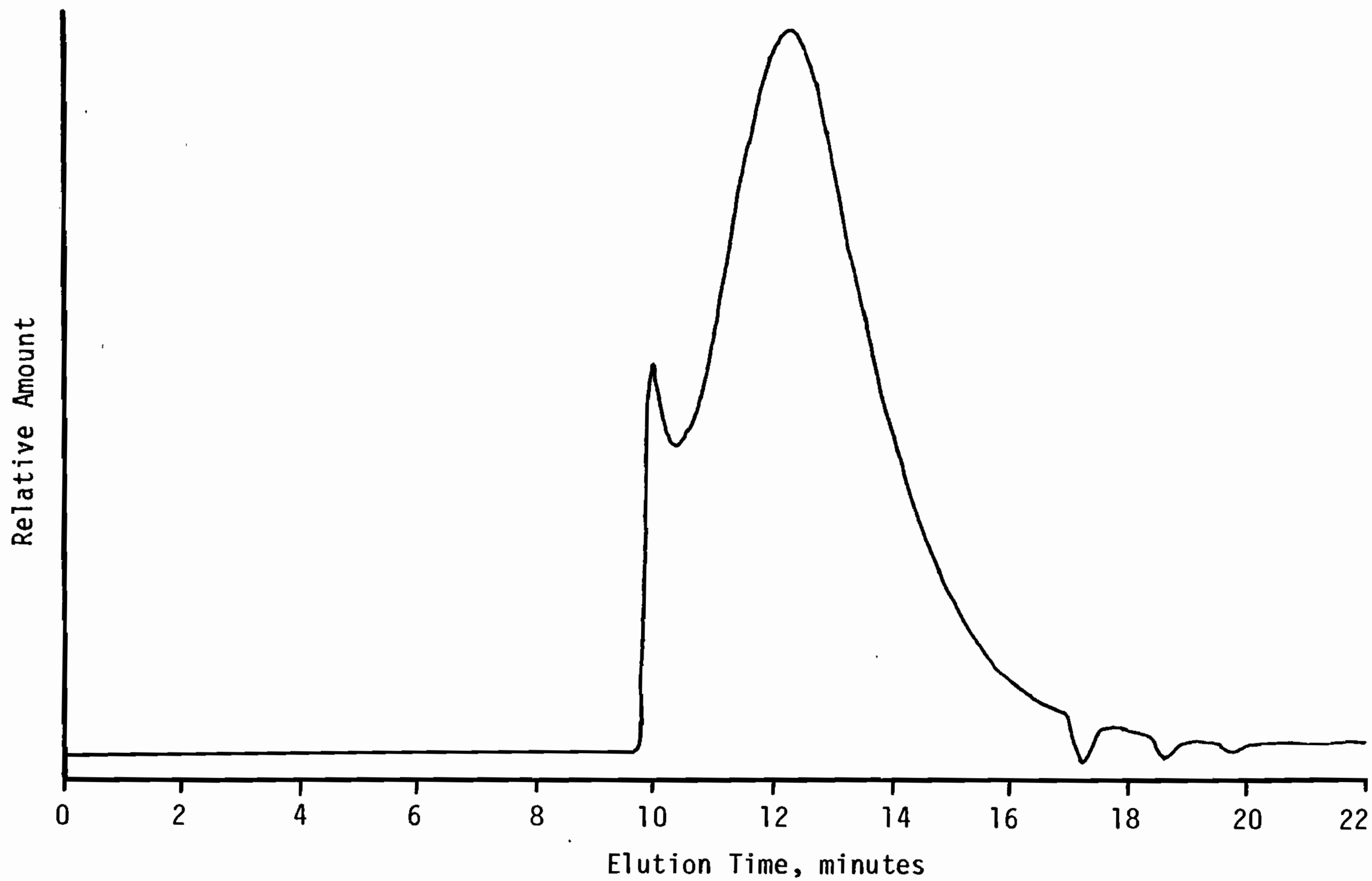

Figure D38. Chromatogram of Asphalt E, AC-20, Virgin Asphalt Cement from Lufkin.

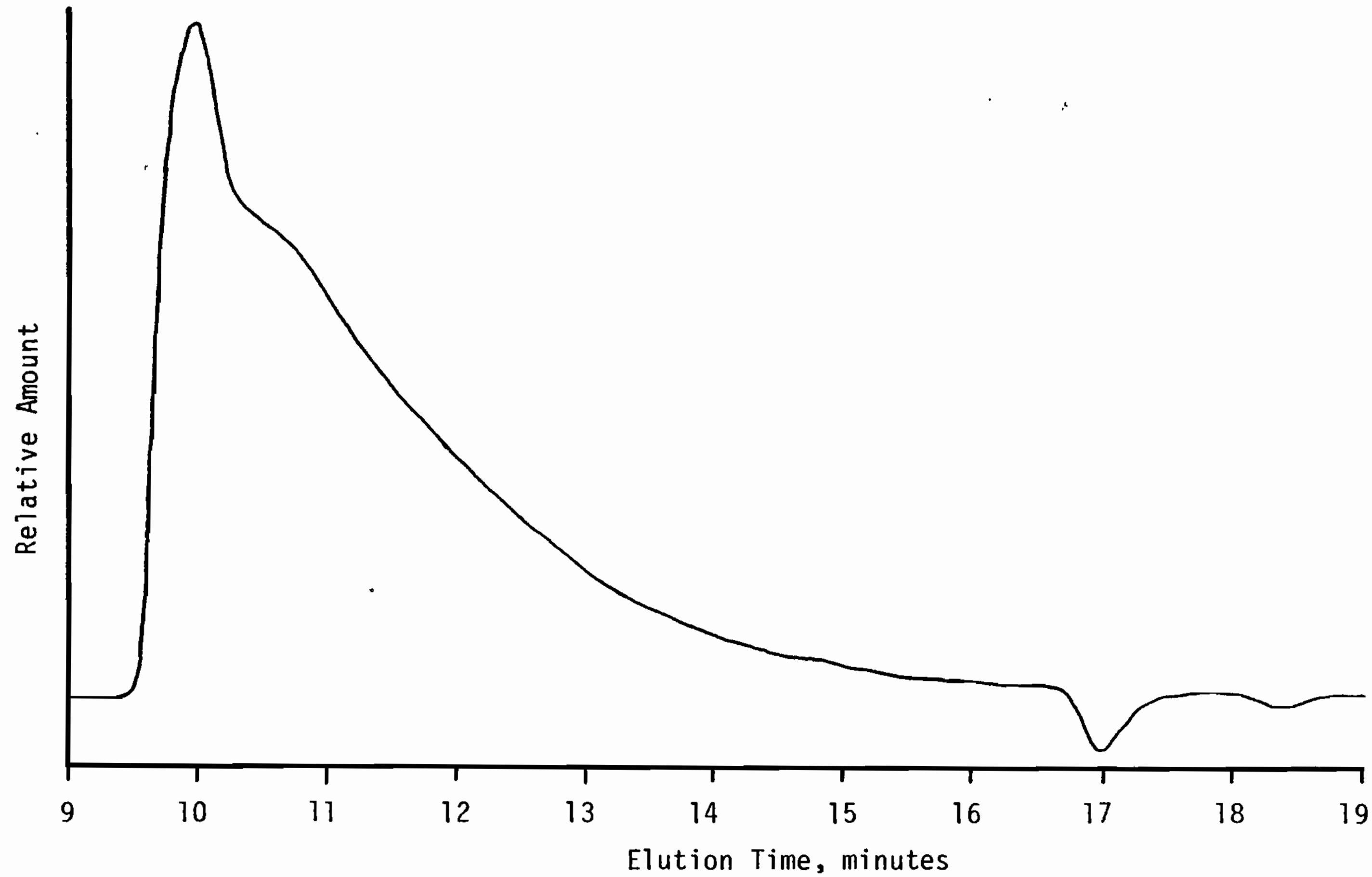

Figure D39. Chromatogram of Asphalt A, AC-20, Extracted from Lufkin Lab Molded Samples.

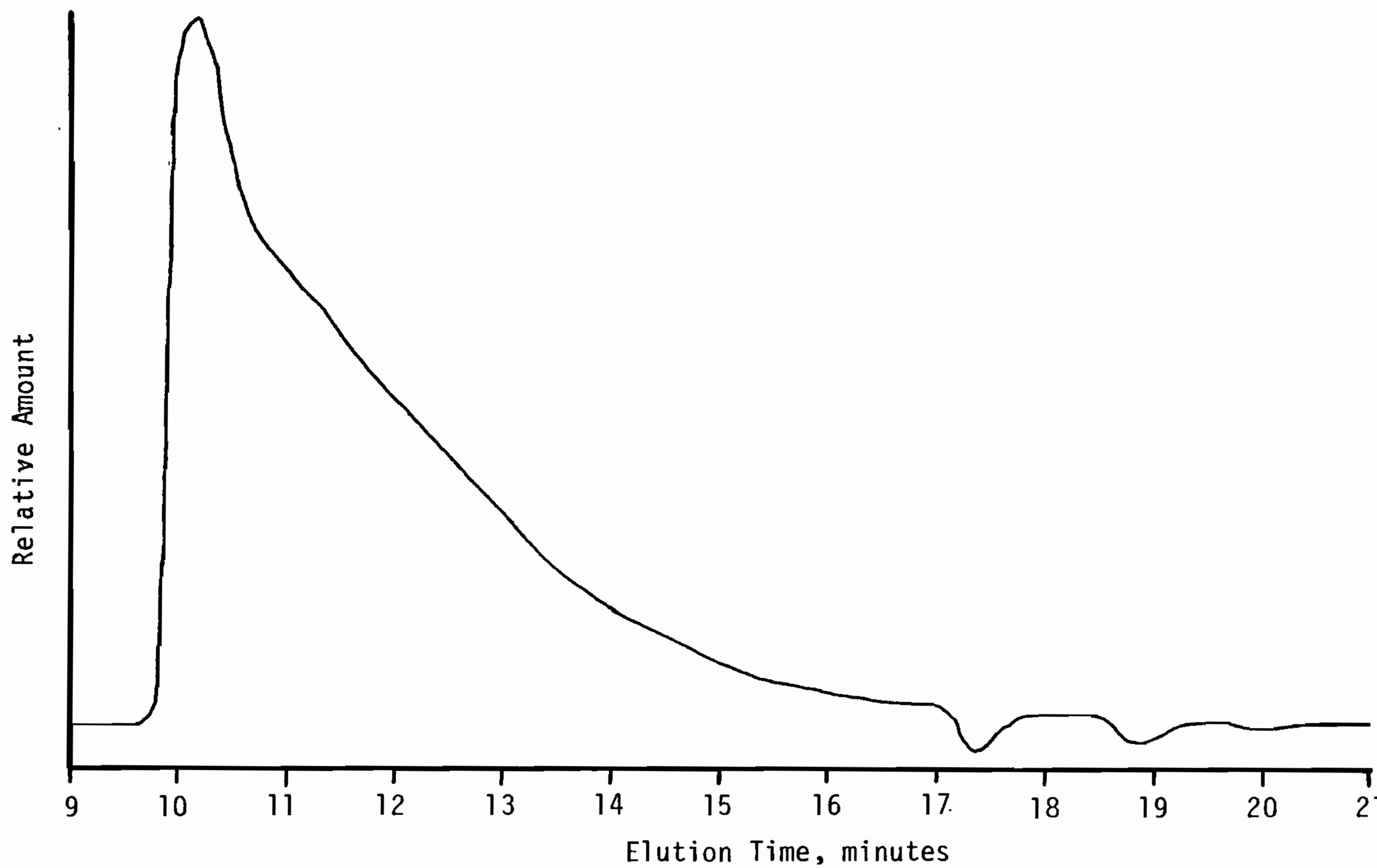

Figure D40. Chromatogram of Asphalt A, AC-20, Extracted from Lufkin Field Cores.

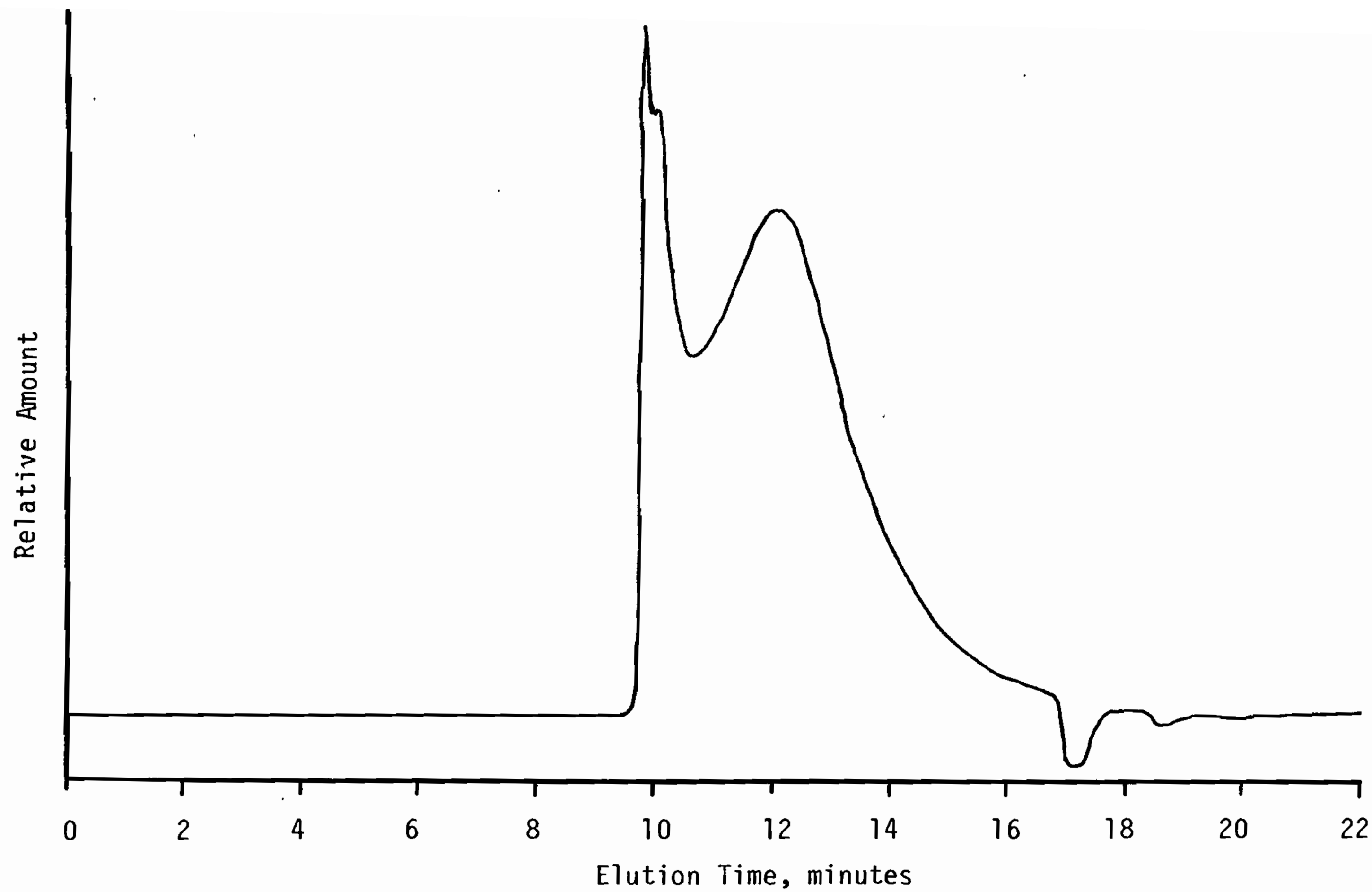

Figure D41. Chromatogram of Asphalt B, AC-20, Extracted from Lufkin Field Cores.

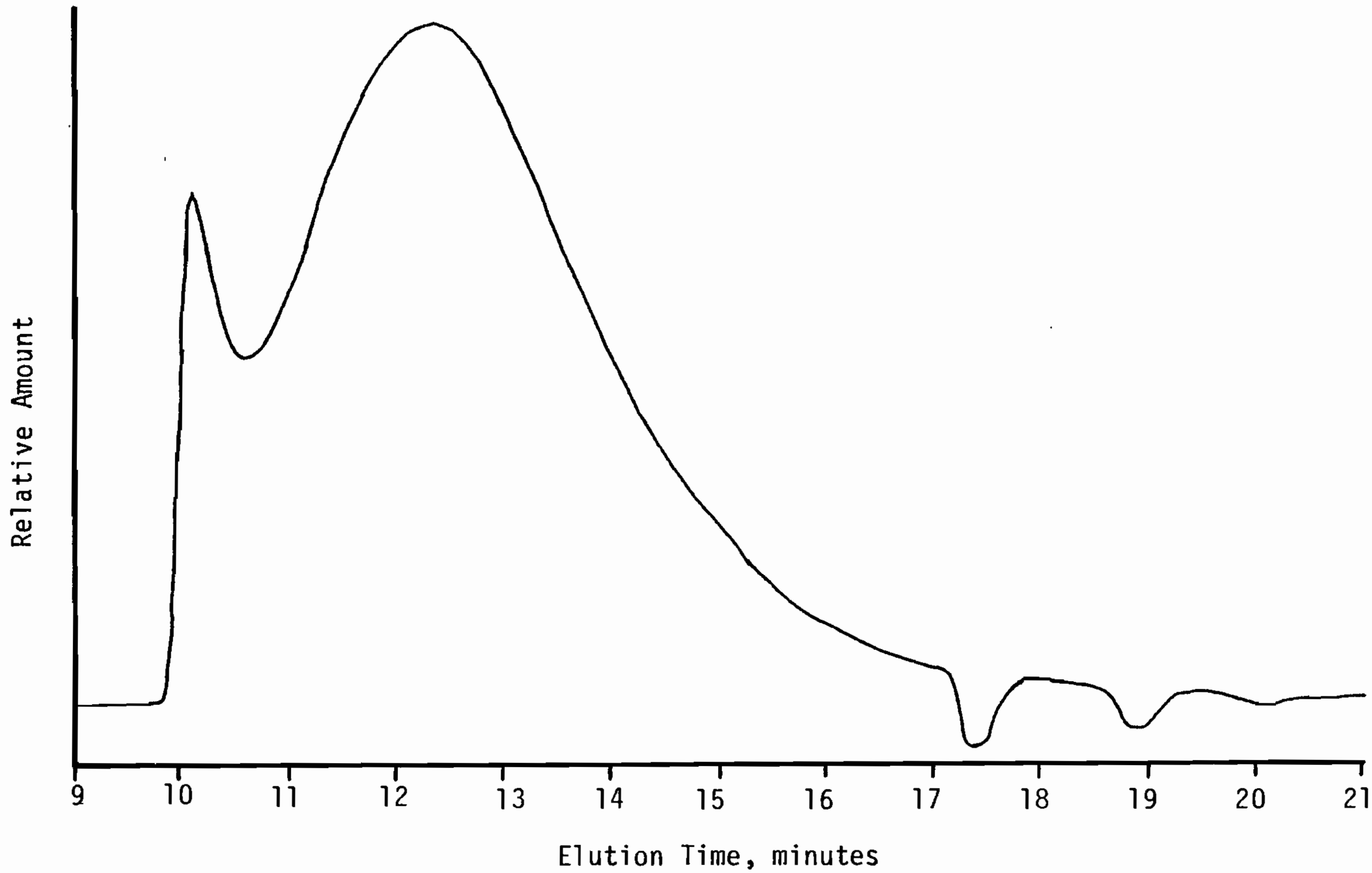

Figure D42. Chromatogram of Asphalt C, AC-20, Extracted from Lufkin Lab Molded Samples.

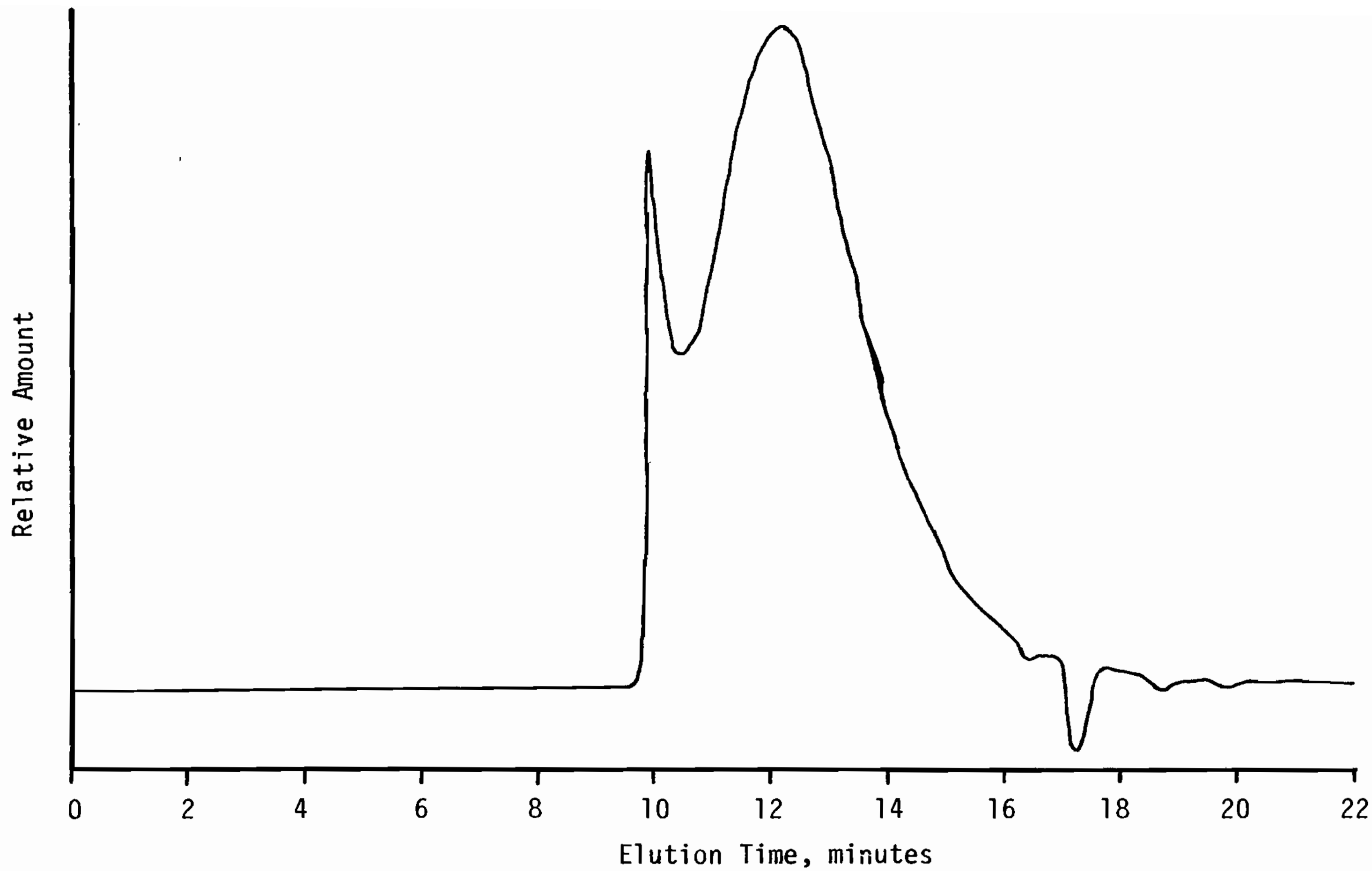

Figure D43. Chromatograph of Asphalt C, AC-20, Extracted from Lufkin Field Cores.

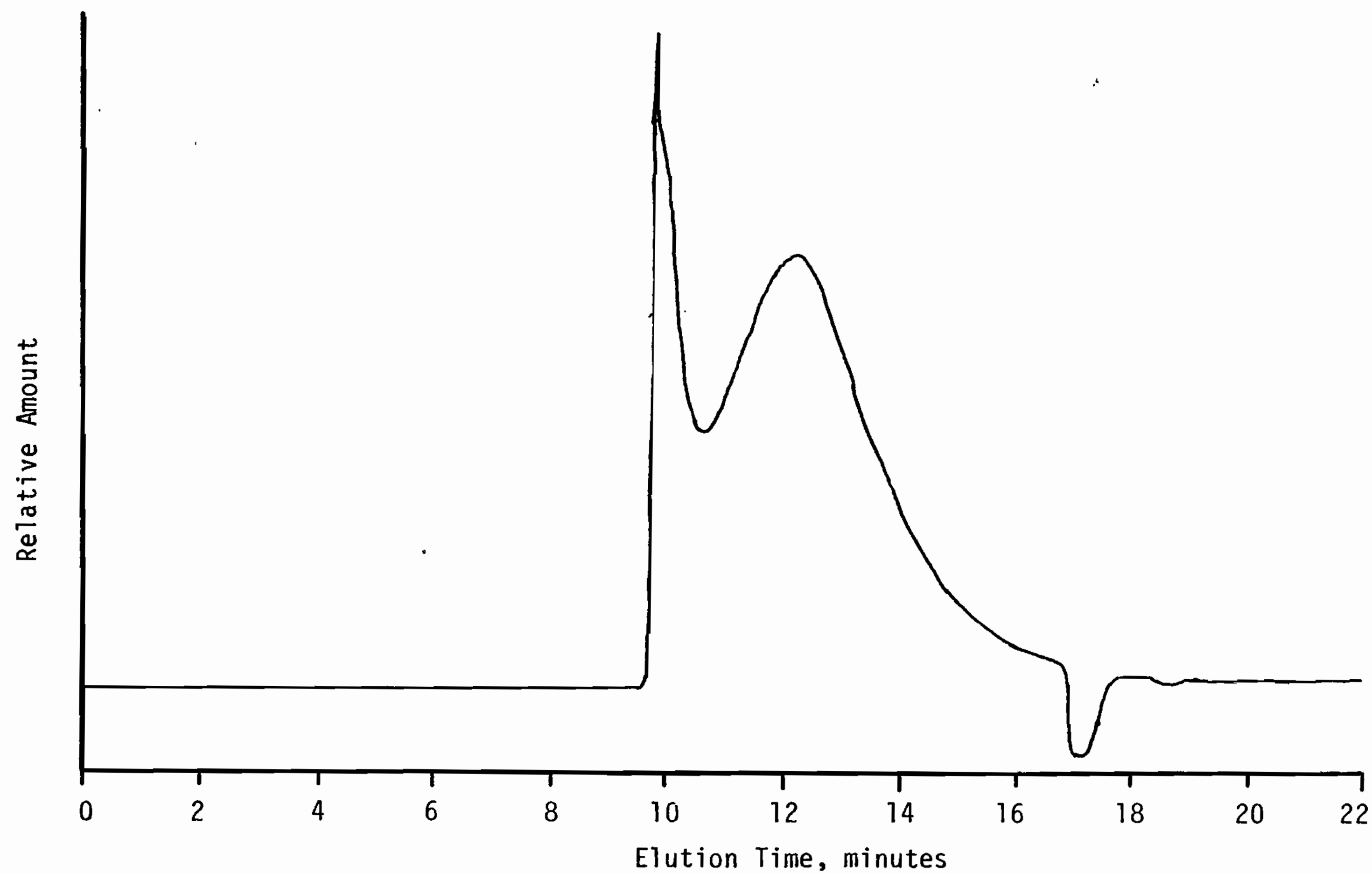

Figure D44. Chromatogram of Asphalt D, AC-10, Extracted from Lufkin Field Cores.

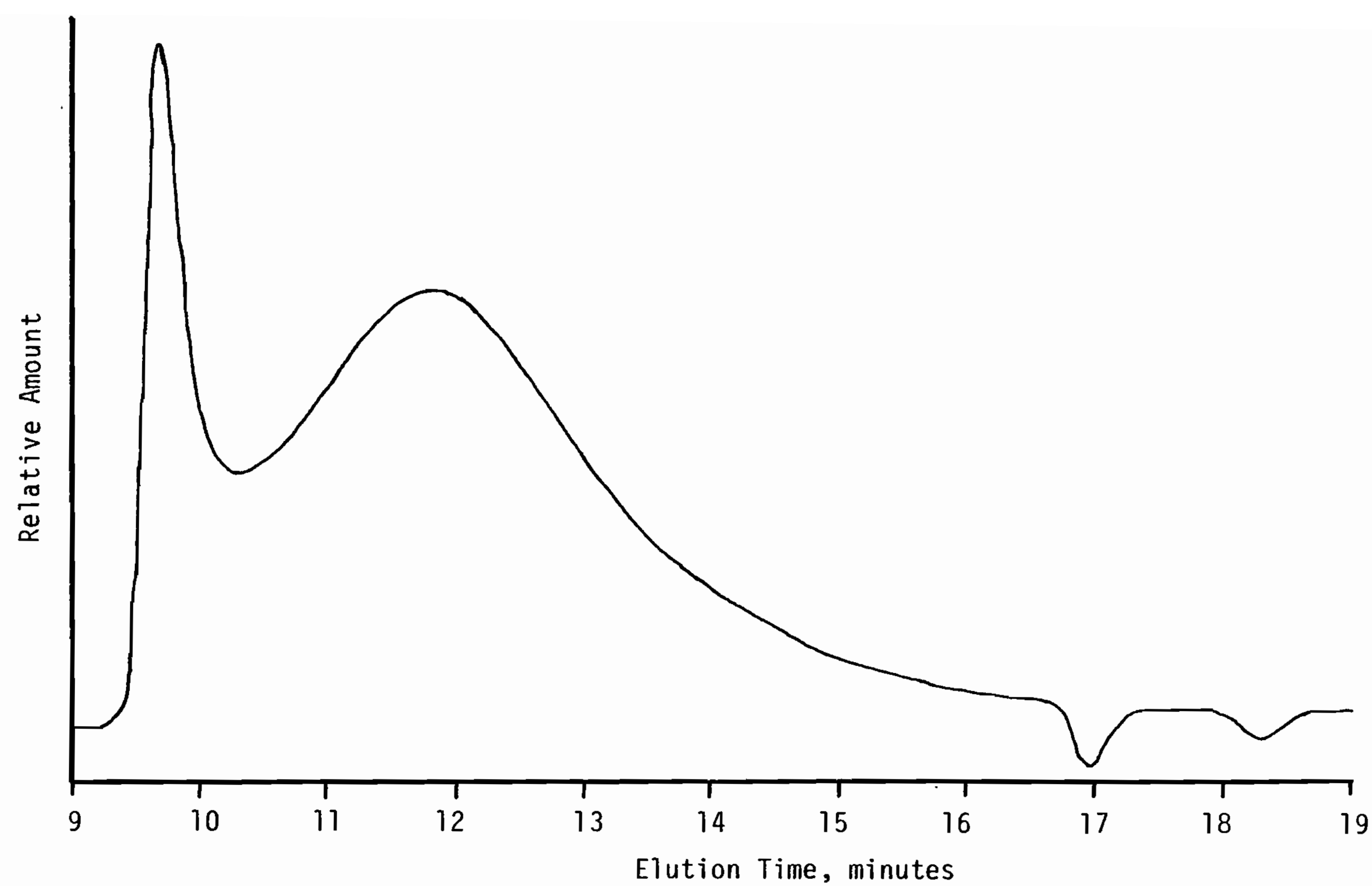

Figure D45. Chromatogram of Asphalt D, AC-20, Extracted from Lufkin Lab Molded Samples.

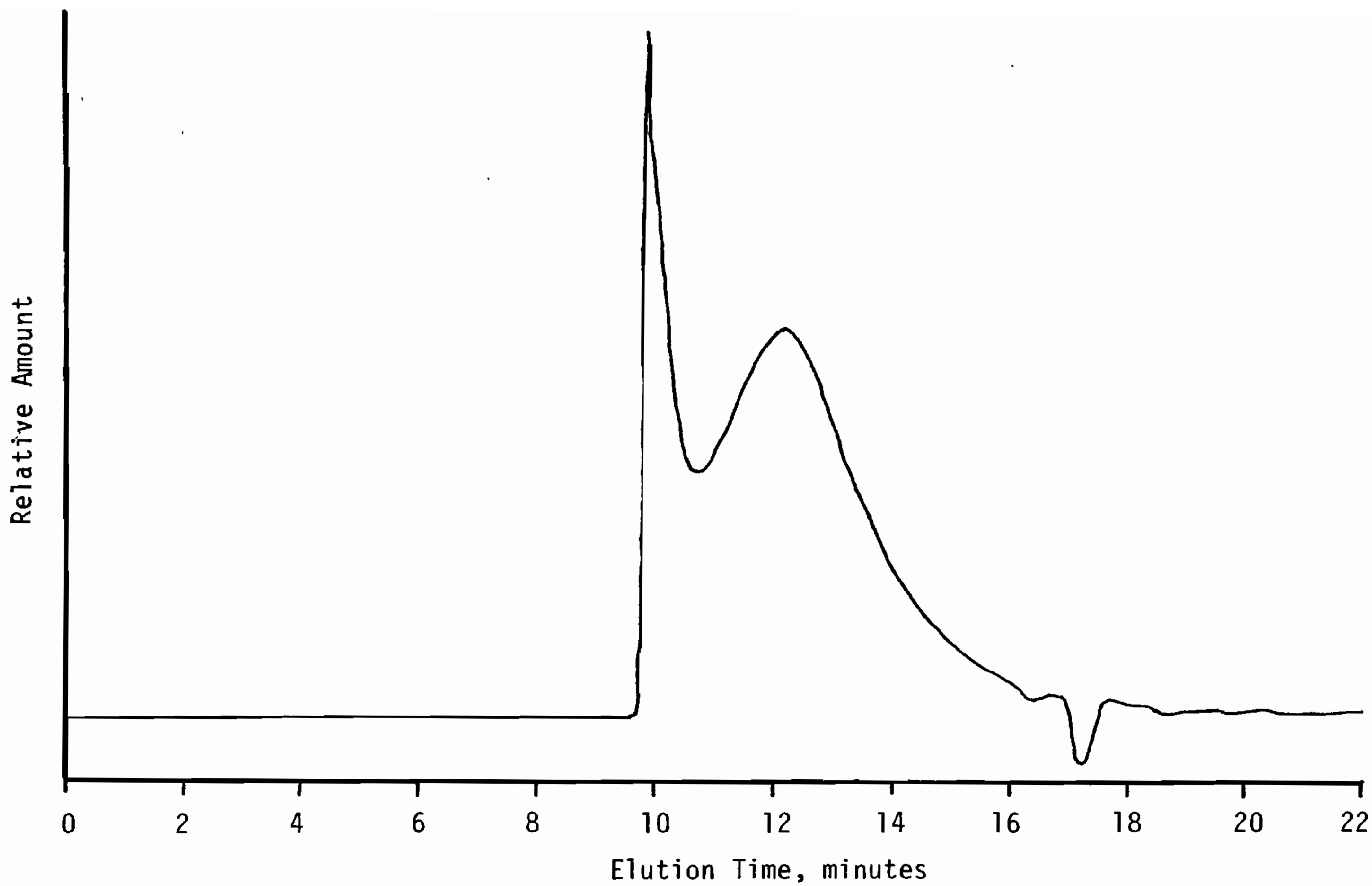

Figure D46. Chromatogram of Asphalt D, AC-20, Extracted from Lufkin Field Cores.

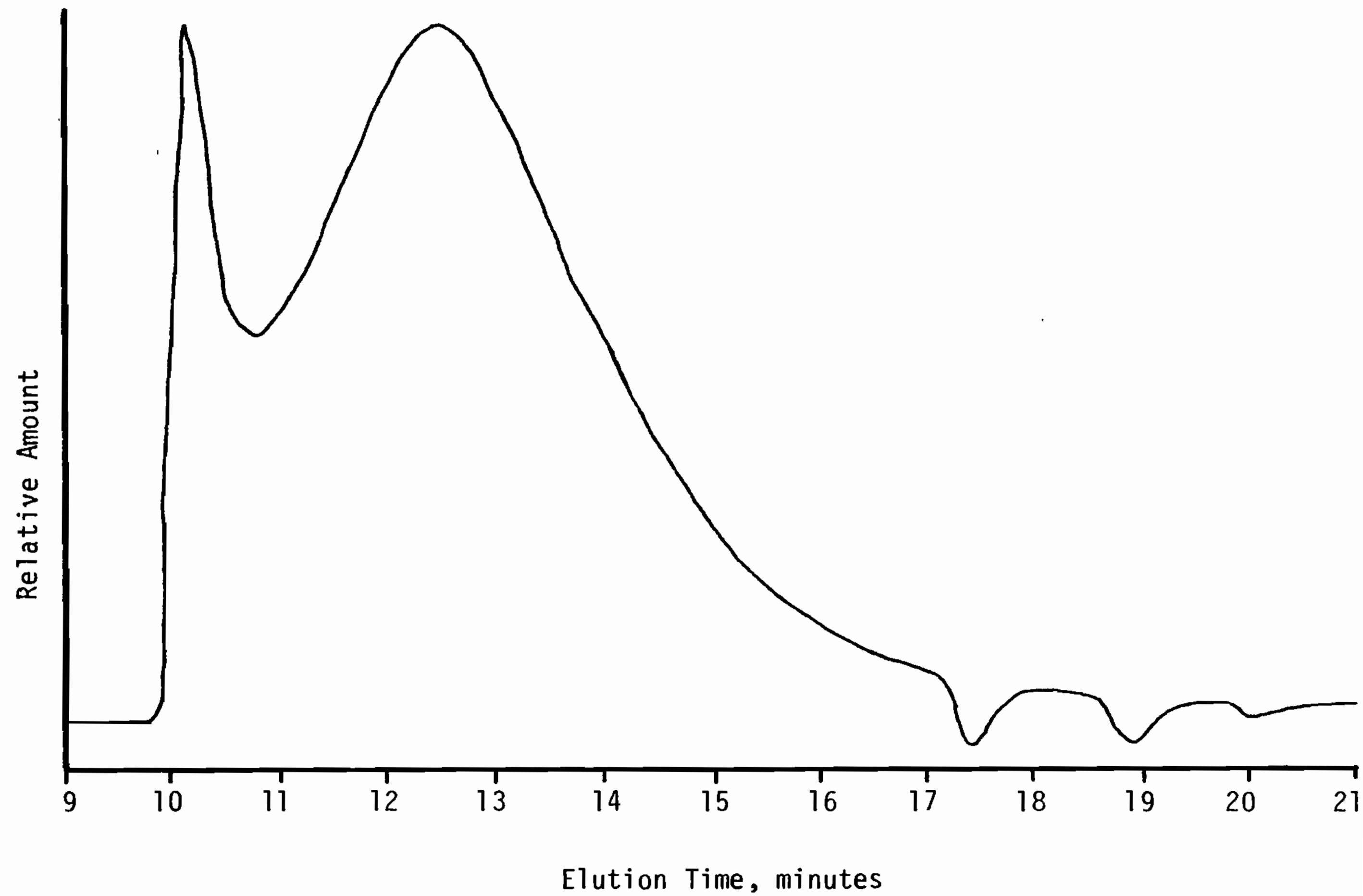

Figure D47. Chromatogram of Asphalt E, AC-20, Extracted from Lufkin Field Cores.