# Aging of Bituminous Concrete

by

Jack E. Stephens
Professor of Civil Engineering

Wimpy Santosa
Research Assistant

JHR 92-211 Project 87-5

This research was sponsored by the Joint Highway Research Advisory Council (JHRAC) of the University of Connecticut and the Connecticut Department of Transportation and was carried out in the Civil Engineering Department of the University of Connecticut.

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the University of Connecticut or the Connecticut Department of Transportation. This report does not constitute a standard, specification, or regulation.

**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No.<br>JHR 92-211 | 2. Government Accession No. | 3. Recipient's Catalog No. |

4. Title and Subtitle

# Aging of Bituminous Concrete

5. Report Date
July 14, 1992

6. Performing Organization Code

7. Author(s)
Jack E. Stephens and Wimpy Santosa

8. Performing Organization Report No.
JHR 92-211

9. Performing Organization Name and Address
University of Connecticut
Department of Civil Engineering
191 Auditorium Road, Box U-37 TI
Storrs, CT 06269

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Connecticut Department of Transportation
280 West Street
Rocky Hill, CT 06067-0207

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Much of the age hardening of the binder in bituminous binder is due to oxidation. The source of oxygen must be the air in the pavement voids. In order to determine the relationship between voids level and aging, four inch diameter samples were molded. The weight was held constant and the height varied so as to result in a series with voids levels from 5% to 15% by one percent intervals. The source material came from routine production of ConnDOT class 1 and class 2 gradations at two local plants. One used natural rounded glacial gravel and one used crushed quarry stone. The molded samples were left in the mold sleeves which were fitted with gasketed end plates through which a small air pressure could be applied to the end of the sample. The samples were placed in a 140°F oven for 48 hours with .1 psi air pressure applied. After extraction, the viscosity and penetration of the binder before and after aging were measured and compared. Penetration results indicated that for voids below 9% and above 13% all mixes aged about the same amount, but between 9 and 13 the class 1 mixes aged faster than the class 2. The viscosity results indicated that the voids level at which the rate of hardening increased fell between 11 and 13 % and that the class 1 gravel mix aged more than the others.

| | |
|---|---|
| 17. Key Words<br>Asphalt, binder, oxidation, age-hardening voids, penetration retained, aging index | 18. Distribution Statement<br>No restrictions |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>59 | 22. Price |

**Form DOT F 1700.7** (8-72)

**Reproduction of completed page authorized**

# ACKNOWLEDGEMENT

The authors would like to acknowledge the Connecticut Department of Transportation for funding this research. They would also like to thank Ms. Stephanie G. Merrall of the Transportation Institute of the University of Connecticut for providing them publications related to this study.

# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimetres | mm |
| ft | feet | 0.305 | metres | m |
| yd | yards | 0.914 | metres | m |
| mi | miles | 1.61 | kilometres | km |
| | | **AREA** | | |
| in$^2$ | square inches | 645.2 | millimetres squared | mm$^2$ |
| ft$^2$ | square feet | 0.093 | metres squared | m$^2$ |
| yd$^2$ | square yards | 0.836 | metres squared | m$^2$ |
| ac | acres | 0.405 | hectares | ha |
| mi$^2$ | square miles | 2.59 | kilometres squared | km$^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | millilitres | mL |
| gal | gallons | 3.785 | Litres | L |
| ft$^3$ | cubic feet | 0.028 | metres cubed | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | metres cubed | m$^3$ |

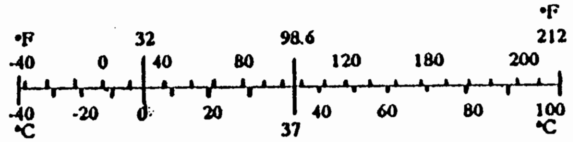
NOTE: Volumes greator than 1000 L shall be shown in m$^3$.

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 | Celcius temperature | °C |

*SI is the symbol for the International System of Measurement

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimetres | 0.039 | inches | in |
| m | metres | 3.28 | feet | ft |
| m | metres | 1.09 | yards | yd |
| km | kilometres | 0.621 | miles | mi |
| | | **AREA** | | |
| mm$^2$ | millimetres squared | 0.0016 | square inches | in$^2$ |
| m$^2$ | metres squared | 10.764 | square feet | ft$^2$ |
| ha | hectares | 2.47 | acres | ac |
| km$^2$ | kilometres squared | 0.386 | square miles | mi$^2$ |
| | | **VOLUME** | | |
| mL | millilitres | 0.034 | fluid ounces | fl oz |
| L | litres | 0.264 | gallons | gal |
| m$^3$ | metres cubed | 35.315 | cubic feet | ft$^3$ |
| m$^3$ | metres cubed | 1.308 | cubic yards | yd$^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams | 1.102 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |



# Table of Contents

Standard Title Page .................................... i
Technical Report Documentation ............................. ii
Acknowledgements .................................... iii
Metric Conversion .................................... iv
Table of Contents .................................... v
List of Tables .................................... vi
List of Figures .................................... vii

I. Introduction .................................... 1
II. Objectives .................................... 2
III. Review of Bituminous Aging Studies .................... 2
IV. Selection of Laboratory Aging Method .................... 5
V. Materials .................................... 5
VI. Specimen Preparation .................................... 12
VII. Aging Procedure .................................... 14
VIII. Extraction and Recovery of Asphalt .................... 14
IX. Evaluation Procedure .................................... 14
X. Results and Discussion .................................... 16
XI. Conclusions .................................... 48
XII. References .................................... 49

# List of Tables

Table 1. Mixtures Studied .............................. 6
Table 2. Gradation of Class 1 Asphalt Concrete Mixtures .. 6
Table 3. Gradation of Class 2 Asphalt Concrete Mixtures .. 7
Table 4. Properties of Recovered Asphalt Before Laboratory Aging ............................................. 7
Table 5. Specific Gravity of the Material ................ 12
Table 6. Penetration Test Results ........................ 17
Table 7. Percent Penetration Retained (PPR) .............. 17
Table 8. Analysis of Variance for Dependent Variable PPR . 18
Table 9. SNK Test for Means of PPR by Mixture Type ....... 18
Table 10. SNK Test for Means of PPR by Air Void Level ..... 20
Table 11. Viscosities Measured at 32° F (in Giga-poises) .. 21
Table 12. Viscosities Measured at 77° F (in mega-poises) .. 22
Table 13. Viscosities Measured at 140° F (in kilo-poises) . 22
Table 14. Aging Index at 32° F ............................ 35
Table 15. Aging Index at 77° F ............................ 36
Table 16. Aging Index at 140° F ........................... 36
Table 17. Analysis of Variance for Dependent Variable AI .. 37
Table 18. SNK Test for Means of AI by Mixture Type ........ 37
Table 19. SNK Test for Means of AI by Test Temperature .... 38
Table 20. SNK Test for Means of AI by Air Void Level ...... 38
Table 21. Critical Voids Determined by Various Procedures . 39
Table 22. VTS of the Aged Asphalt ......................... 43
Table 23. Nonparametric Sign Test Results ................ 48

# List of Figures

Figure 1. Gradation of Mixture A (Class 1) ................ 8
Figure 2. Gradation of Mixture B (Class 2) ................ 9
Figure 3. Gradation of Mixture C (Class 1) ................ 10
Figure 4. Gradation of Mixture D (Class 2) ................ 11
Figure 5. Schematic Illustration of Gyratory Machine ...... 13
Figure 6. PPR versus Air Void ............................. 19
Figure 7. Viscosity at 32° F versus Air Void (Mixture A) .. 23
Figure 8. Viscosity at 32° F versus Air Void (Mixture B) .. 24
Figure 9. Viscosity at 32° F versus Air Void (Mixture C) .. 25
Figure 10.Viscosity at 32° F versus Air Void (Mixture D) .. 26
Figure 11.Viscosity at 77° F versus Air Void (Mixture A) .. 27
Figure 12.Viscosity at 77° F versus Air Void (Mixture B) .. 28
Figure 13.Viscosity at 77° F versus Air Void (Mixture C) .. 29
Figure 14.Viscosity at 77° F versus Air Void (Mixture D) .. 30
Figure 15.Viscosity at 140° F versus Air Void (Mixture A).. 31
Figure 16.Viscosity at 140° F versus Air Void (Mixture B).. 32
Figure 17.Viscosity at 140° F versus Air Void (Mixture C).. 33
Figure 18.Viscosity at 140° F versus Air Void (Mixture D).. 34
Figure 19.AI at 32° F versus Air Void ..................... 40
Figure 20.AI at 77° F versus Air Void ..................... 41
Figure 21.AI at 140° F versus Air Void .................... 42
Figure 22.VTS versus Air Void (Mixture A) ................. 44
Figure 23.VTS versus Air Void (Mixture B) ................. 45
Figure 24.VTS versus Air Void (Mixture C) ................. 46
Figure 25.VTS versus Air Void (Mixture D) ................. 47

# I. Introduction

Transportation facilities make up a large portion of the 1991 infrastructure. In the small state of Connecticut, there are over 30,000 miles of roadways. Continuing development increases this mileage by over 2% annually. The state currently spends about 70 million dollars a year to maintain its roads [1].

A major factor in the life of a bituminous pavement is age hardening of the binder. Over the years as wheel loads increased, it has been necessary to increase mix stability. A mix with a Marshall stability of 800 thought adequate in the early fifties would rut if subjected to today's loads. The stiffer mixes resist shoving and rutting well but require more compactive effort. Further stiffening brought about by age hardening can quickly result in brittleness and cracking from relatively small movements. In the fifties, the average life of bituminous pavements was fifteen years [2]. The literature has reports of serious cracking in a little as eight years [3] and reflection cracks have been found in local overlays only months old. A modest reduction in pavement life could result in a sharp increase in the state pavement expenditures in future years.

An example of such a problem is graphically illustrated locally on road I-384 around Willimantic. The cracking of the asphalt surface over the concrete bridge decks is as intense as that of the adjacent pavement, yet the flexing over the concrete due to loading is minimal. The crack pattern geometry does not indicate failure from loading and, therefore, must be due to environmental factors.

The problem in the previous paragraph can be explained based on the relative coefficient of thermal expansion of aggregate and asphalt and the effect of traffic on the pavement. The coefficient of expansion for asphalt is about 18 times that for stone. As day progresses, the sun warms the pavement and both asphalt and aggregate expand. The asphalt moves with respect to the aggregate and the resistance to movement is less in the vertical direction. The asphalt flows upward and tends to raise the upper portion of the aggregate with it. During the night, the temperature falls and the materials contract. The cohesion of the asphalt cannot pull the aggregate as tight as originally compacted by the roller. Consequently, the voids in the pavement steadily increase until air can pass through the pavement causing the asphalt film in the pavement system to age and the pavement to become hard, brittle, and susceptible to cracking failures. Traffic tends to recompact the pavement layer slowing the level of void increase. The traffic on this particular road apparently was not enough to recompact the pavement.

It is possible to make a bituminous concrete mixture that, upon compaction, would have no air void and so should not age. However, the asphalt content of such a mixture would be high, the stability low, and under heavy traffic would rut and shove. Reducing the asphalt and fines of such a mix would increase the stability but would probably increase the air voids and hasten the air hardening. Over the years, many authorities have noted that mixes are a balance between stability and durability and that increases in either are often accompanied by a reduction in the other [8,9]. Specifying limits for air voids is an attempt to insure durability without a lose in stability. The low limit is intended to ensure adequate space for the binder should traffic cause further compaction. The upper limit is intended to ensure that air cannot circulate through the pavement aging the binder. There is almost no information in the literature that can be used to determine the limiting voids level if air hardening is to be avoided. air aging.

Traditionally, the durability of asphalt pavement performance has been based on the properties of neat asphalt used in the mixture. However, recent studies show that using only the properties of the neat asphalt prior to being mixed with aggregates and compacted into pavement is inadequate. It was, therefore, the intent of this study to obtain a better understanding of the aging of compacted asphalt aggregate mixtures.

## II. Objectives

The purpose of this study was to obtain a better understanding of the aging of bituminous concrete associated with the air void content in the mixture. The study was intended to determine what minimum level of voids in the mixture is necessary for the access of oxygen to cause serious aging. The results will provide a rational means for establishing a maximum value for air void content if aging is to be controlled.

The research approach included preparing samples at various air void contents, aging the samples artificially, and evaluating the properties of the asphalt binder before and after the artificial aging. The relationship between the air void and the aging rate was investigated. A break point in a plot of asphalt rheological property versus air voids would indicate the critical void for the pavement.

## III. Review of Bituminous Aging Studies

Aging is the term usually used to describe the phenomenon of hardening. Other terms commonly used are age-hardening and embrittlement [6]. With time, decreases in the penetration or increases in viscosity are indications of the changes occurring in the binder [7,8].

Heat and the presence of oxygen appear to be the major factors controlling the rate of hardening. Based on combinations of these two factors, the aging of a binder after refining can be divided into three phases. Until introduced into the mixer, the binder is always in some form of heated container. In bulk, the lack of access to oxygen prevents hardening even at the elevated temperature. The first phase of active hardening occurs during mixing and placing. The mix temperature would be in the 275° F to 325° F range and the asphalt is spread in thin films over the aggregate. With no prior exposure, this is the first point at which vaporization of lighter constituents can occur. Aeration during mixing and placing permits access to unlimited air and causes oxidation.

Once spread, compacted, and cooled, a new phase of aging starts. The University of Connecticut pavement researchers have measured winter pavement surface temperature below 0° F and summer temperatures after a day of sunshine of 175° F. The access to oxygen is controlled by film thickness and air permeability of the layer. Aging in service is slow compared to the mixing phase.

Roberts et al (1991) listed six factors that have been reported to contribute to the aging of asphalt binder during hot-mix process and/or during service in the field. These factors are oxidation, volatilization, polymerization, thixotropy, syneresis, and separation. The definitions of these terms are given in the following paragraphs [8].

Oxidation is the reaction of oxygen with the asphalt binder. The oxidation rate is influenced by the chemical composition of the asphalt, the temperature, and the access to oxygen. The asphalt oxidation change is speeded up by elevated temperatures.

Volatilization is the evaporation of the lighter constituents from the asphalt. It is greatly affected by temperatures. Volatilization is a significant factor contributing to the aging of asphalt mixture in the hot-mix process.

Polymerization is a combining of like molecules to form larger molecules, causing a progressive hardening. The significance of the polymerization during low temperature aging of asphalt in pavements has been speculated in the literature. However, there is no scientific evidence to support this argument.

Thixotropy is a progressive hardening caused by molecular structuring within the asphalt binder over period of time. Thixotropic hardening is also called steric hardening which usually occurs in a pavement with little or no traffic. The thixotropic hardening rate is a function of asphalt chemical composition.

Syneresis is an oil exudation reaction in which the thin oily components of the asphalt are exuded to the surface of the asphalt film. The loss of the oily components causes the asphalt to become harder.

Separation is the removal of the oily constituents, resins, or asphaltenes from the asphalt cement. One cause is selective absorption by porous aggregates in the mixture.

Some other factors were listed by Traxler (1963) including photo-oxidation and photo-chemical reaction due to direct or reflected light, changes by nuclear energy, water, chemical reaction with aggregates, microbiological deterioration, and adsorption of heavy asphalt components on the surface of the aggregates. Traxler provided data to support his argument; however, he also stated that some factors were not given experimental consideration [9].

More recently, Petersen (1984) presented three major composition-related factors which influence the aging of asphalt [10]. These factors are :

1. the loss of oily components through volatilization and absorption by porous aggregates;
2. the change in asphalt chemical composition by reaction with oxygen in the air; and,
3. the molecular structuring that produces thixotropic effects or steric hardening.

The majority of researchers studying the aging of asphalt and asphalt mixtures have focused their investigations to these factors given by Petersen [6].

Two developments in the past had a direct bearing on the solution of the aging problem [11]. The first was the trend in the late 1930s to use higher penetration grade of asphalts. It was found that the use of softer asphalt binder in hot-laid, plant-mixed, pavements would result in better performance, longer life, and less cracking [12,13]. The second was the effort by several researchers to develop laboratory aging tests that could predict asphalt quality and, with proper specification requirements, assure better pavement performance.

Early work on the laboratory aging tests emphasized asphalt binder studies and, in particular, the effect of extended heating. The Thin Film Oven Test (TFOT) and the Rolling Thin Film Oven Test (RTFOT), both now ASTM standardized procedures, have been commonly used to evaluate the relative aging of asphalts.

Compared to research on asphalt binder, there has been little work on the aging of asphalt mixtures. In addition, there is no standard laboratory conditioning procedure available to simulate changes in asphalt properties during long-term field aging. However, as early as 1903, Dow reported his work on the effect of extended heating on mixtures by comparing the asphalt penetration before heating to that of recovered asphalt after heating [6].

The development of the Abson recovery methods (1933) has had a great influence in research on the aging of asphalt mixtures. The method provides a means of recovering asphalt from hot-mix mixtures both immediately after mixing and after periods of aging in the field [14]. Several studies evaluating the properties of aged asphalt from asphalt-aggregate mixtures have been carried out since, and most of these studies were summarized by Bell [6].

## IV. Selection of Laboratory Aging Method

After reviewing several aging procedures used in the past, it was determined that the laboratory aging method adopted for this study should involve relatively simple equipment and be able to carry out the test with speed and accuracy. In addition, the laboratory procedure selected should correspond as closely as possible to the field condition and be viable for routine use. Since the field aging is predominantly caused by the reaction of the asphalt binder with oxygen in the air, the procedure selected should emphasize the aging due to oxidation.

An oven aging procedure was chosen for this research. This procedure is similar to those performed by Kumar and Goetz [15] and Kim et al [16]. This research differs from those two in that it studies the effect of air void contents on the aging of asphalt mixtures using an oven heating procedure in which oxygen in the air is used to accelerate the aging process. Unlike the one performed by Kim et al, a low air pressure was utilized so that the shape of the specimen and the internal voids in the specimen can be preserved. Changing air void configuration would probably change the rate of aging.

## V. Materials

A total of four mixtures were selected in this study. The coarse aggregate used was either river gravel or trap-rock. The fine aggregates were natural sand and stone sand made from crushed trap rock. The mixtures were supplied by hot-mix plants in Connecticut.

The properties of the mixtures before the laboratory aging were determined by the extraction process. The asphalt content of each mixture is presented in table 1. It was also found that the Aggregate gradations of the mixtures conformed to the Connecticut DOT specification for classes 1 and 2 bituminous concrete mixtures. The results of the sieve analyses on the aggregates along with the Connecticut DOT limits for both classes 1 and 2 are given in tables 2 and 3, respectively. The gradation of each mixture is shown in figures 1, 2, 3, and 4, respectively.

Table 1. Mixtures Studied

| Mixture No. | Class of Mixture | Type of Aggregate | Asphalt Content (%) |
|---|---|---|---|
| A | Class 1 | Gravel | 5.4 |
| B | Class 2 | Gravel | 6.1 |
| C | Class 1 | Trap-rock | 6.3 |
| D | Class 2 | Trap-rock | 6.7 |

Table 2. Gradation of Class 1 Asphalt Concrete Mixtures

| Sieve Size | Percent Passing Mixture A (Class 1) | Percent Passing Mixture C (Class 1) | ConnDOT Specification (Class 1) |
|---|---|---|---|
| 1 " | 100 | 100 | 100 |
| 3/4 " | 100 | 100 | 90-100 |
| 1/2 " | 92.2 | 97.9 | 70-100 |
| 3/8 " | 72.8 | 74.2 | 60-82 |
| 1/4 " | 69.0 | 57.6 | - |
| # 4 | 59.5 | 55.9 | 40-65 |
| # 8 | 47.3 | 43.2 | 28-50 |
| # 50 | 16.7 | 15.3 | 6-26 |
| # 200 | 2.7 | 4.2 | 3-8 |

The properties of the asphalt extracted from the mixture were determined. The results are shown in table 4. The results show that the asphalts recovered from the mixtures with trap-rock (mixtures C and D) had less penetration and higher viscosity values compared to those from mixtures with gravel (mixture A and B). It was also found that the viscosity temperature susceptibility (see page 16) values of the recovered asphalts are about the same except that from mixture C. The asphalt recovered from mixture C has the largest viscosity temperature susceptibility value.

Table 3. Gradation of Class 2 Asphalt Concrete Mixtures

| Sieve Size | Percent Passing Mixture B (Class 2) | Percent Passing Mixture D (Class 2) | ConnDOT Specification (Class 2) |
|---|---|---|---|
| 1/2 " | 100 | 100 | 100 |
| 3/8 " | 99.3 | 95.9 | 90-100 |
| 1/4 " | 75.9 | 71.4 | - |
| # 4 | 64.4 | 62.8 | 55-80 |
| # 8 | 53.2 | 49.0 | 40-64 |
| # 50 | 13.7 | 15.3 | 8-26 |
| # 200 | 3.6 | 4.1 | 3-8 |

Table 4. Properties of Recovered Asphalt Before Laboratory Aging

| Asphalt properties | Recovered from Mixture A | Recovered from Mixture B | Recovered From Mixture C | Recovered From Mixture D |
|---|---|---|---|---|
| Penetration at 77° F (0.1 mm) | 28 | 27 | 23 | 24 |
| Viscosity at 140° F (kilo-poises) | 6.82 | 5.97 | 17.30 | 13.90 |
| Viscosity at 77° F (mega-poises) | 12.40 | 21.90 | 79.50 | 65.60 |
| Viscosity at 32° F (Giga-poises) | 1.30 | 3.65 | 7.61 | 5.63 |
| Viscosity Temperature Susceptibility | 3.24 | 3.49 | 4.04 | 3.28 |

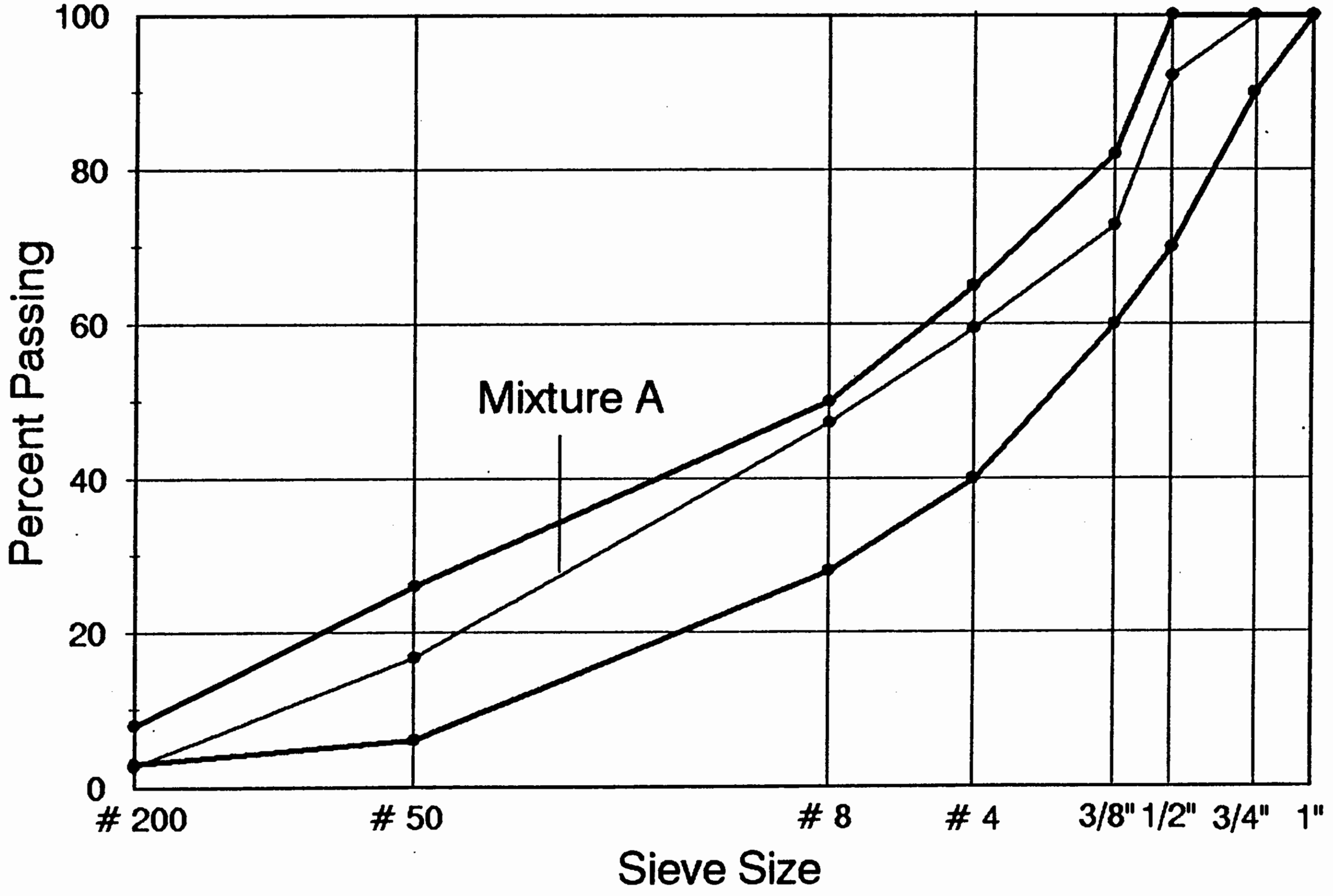


Figure 1. Gradation of Mixture A (Class 1)

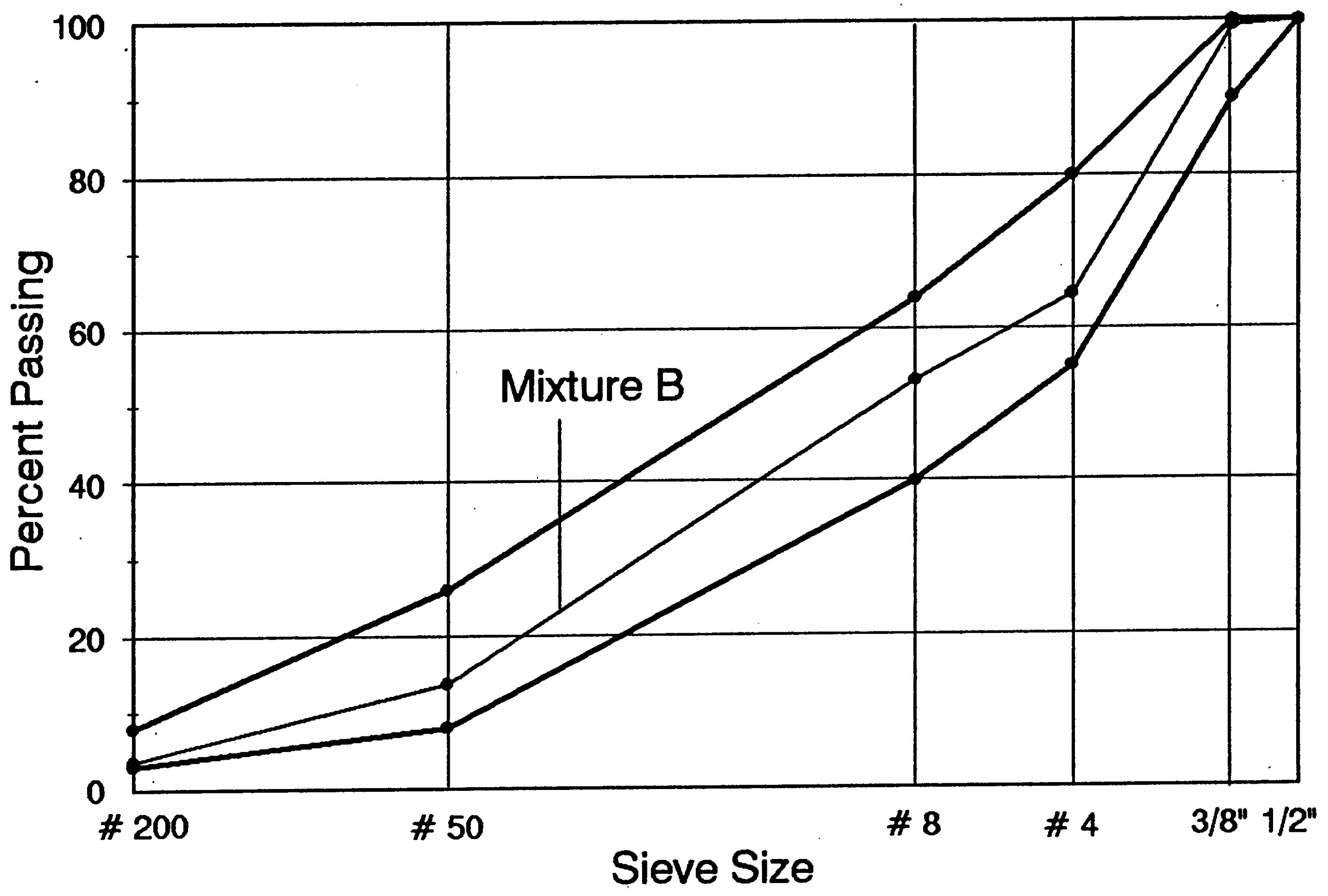


Figure 2. Gradation of Mixture B (Class 2)

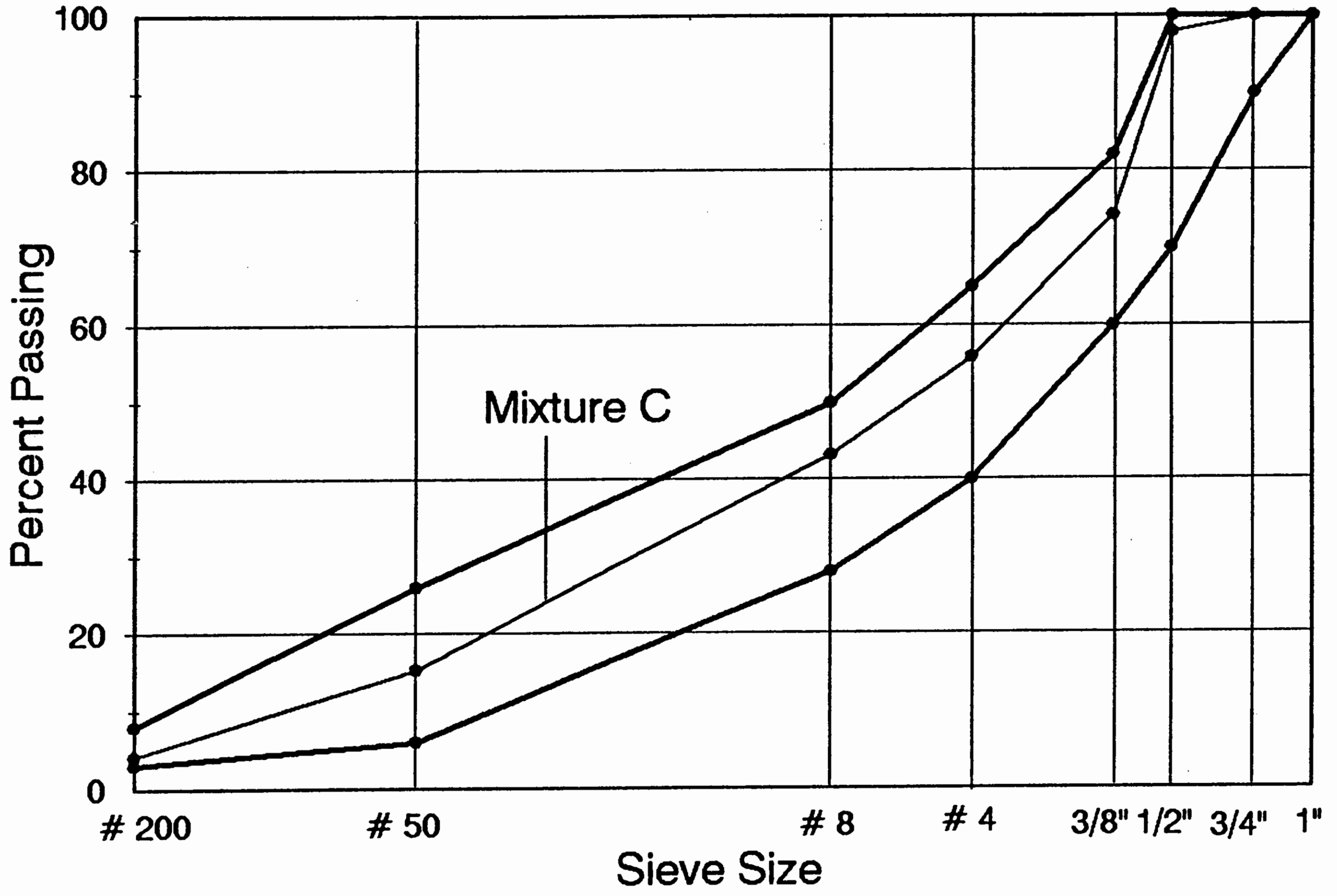


Figure 3. Gradation of Mixture C (Class 1)

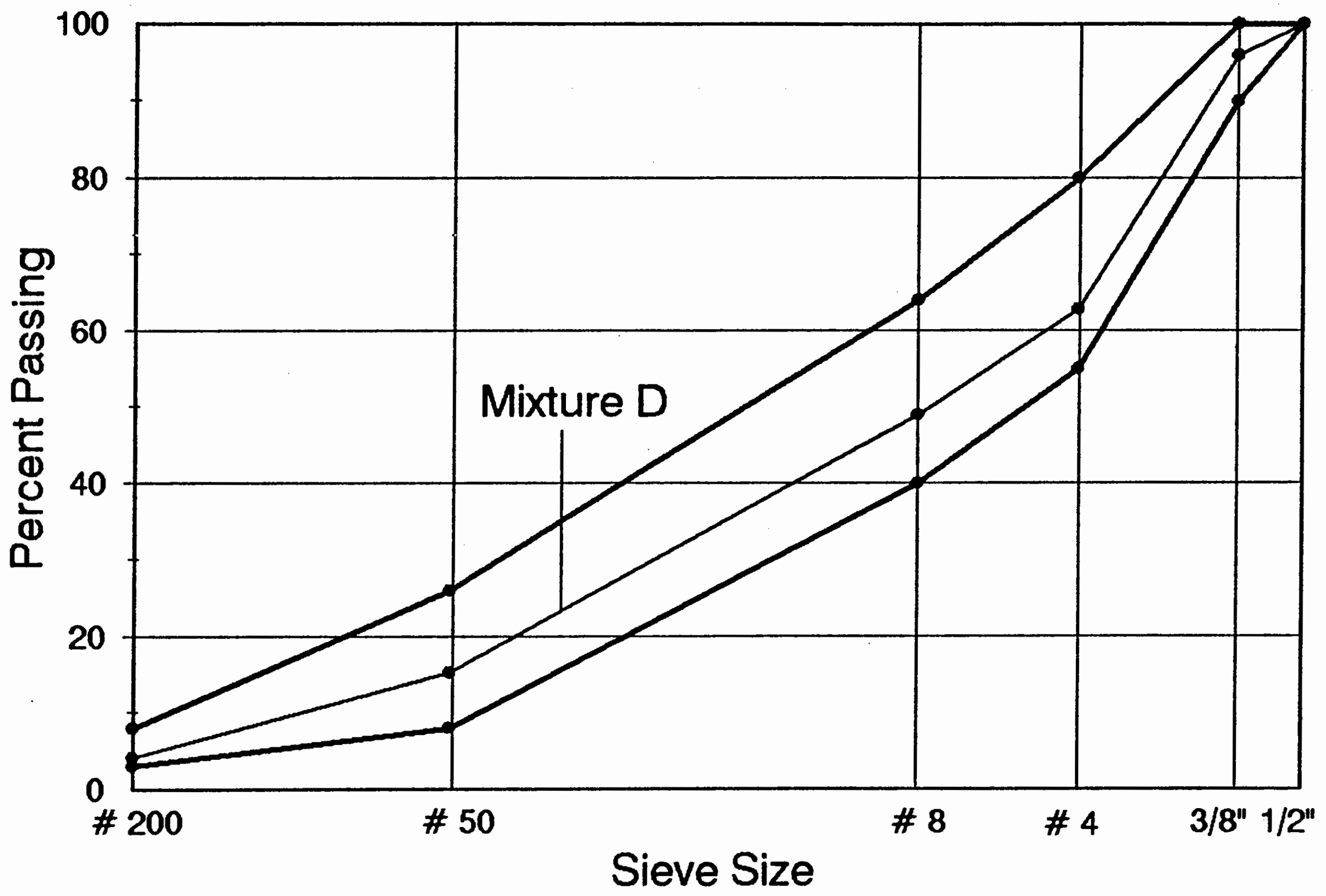


Figure 4. Gradation of Mixture D (Class 2)

## VI. Specimen Preparation

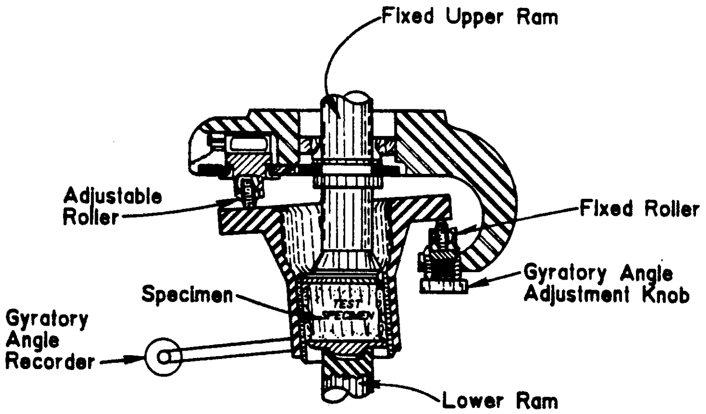
The weight of materials for a zero void specimen was computed for a Marshall sample 2.5 inches in height and 4.0 inches in diameter using the specific gravities of the ingredients recovered from the mix (see table 5). The desired height of the sample was then adjusted according to each predetermined air void content.

Table 5. Specific Gravity of the Material

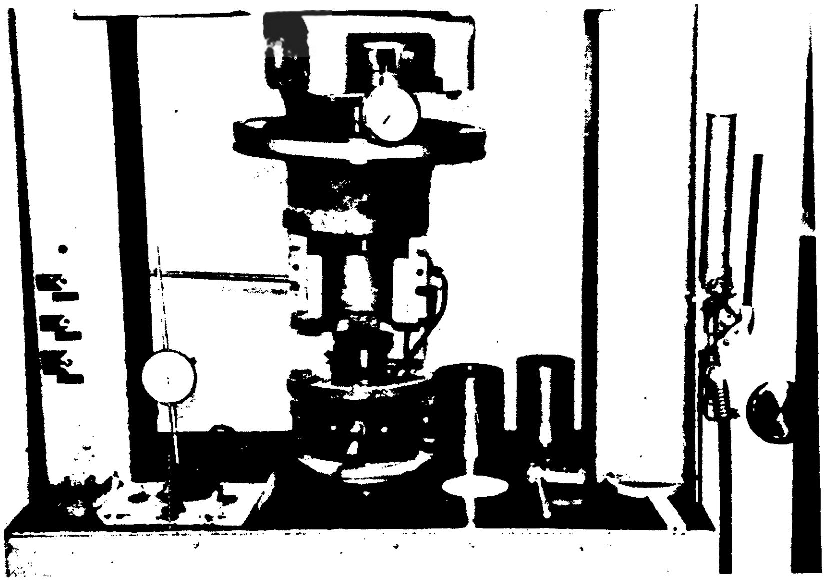
| Type of Material | Specific Gravity |
|---|---|
| Gravel | 2.67 |
| Trap-rock | 2.85 |
| Natural Sand | 2.67 |
| Stone Sand | 2.85 |
| Asphalt | 1.00 |

In this study, each sample contained a total of 1150 grams of mixture. Air void contents were designed to be from 5% to 15% by increments of 1%. Samples were prepared for each of these void contents from all mixtures studied.

A gyratory compaction machine was used to mold the sample with a ram pressure of 15 $kg/cm^2$. The schematic illustration of the gyratory machine is shown in figure 5 [4]. The temperature of the mixture during the molding process was about 275° F. The molding process was stopped when the predetermined height of the specimen associated with the designed void level was obtained.



**Cross-section of Gyratory Compactor Showing Compression and Shear Force Mechanisms**



**Gyratory Testing Machine**

Figure 5. Schematic Illustration of Gyratory Machine

## VII. Aging Procedure

Upon the completion of the compaction process, the specimen was left in the molding sleeve. A plate with an air connection was fitted to the bottom of the mold. The specimen was then subjected to the laboratory aging process.

The aging process selected in this study consisted of placing the entire apparatus in an oven maintained at 140° F for a period of 24 hours. During this period, air was applied to one face of the specimen through the air tube at a low pressure of 0.1 psi. The low air pressure was used in recognition that the differential air pressure from top to bottom of inplace pavement is very small and at the 140° F the use of a higher pressure could change the voids configuration and alter the rate of aging.

At the conclusion of the aging process, the specimen was removed from the apparatus. It was then cooled to room temperature for 24 hours before the asphalt was extracted from the mixture.

## VIII. Extraction and Recovery of Asphalt

After the aged specimen cooled to room temperature, it was broken down and the asphalt in the specimen was extracted following the ASTM D-2172 procedure. The extraction was performed in a Dulin centrifugal extractor.

Methylene chloride was used as a solvent in this process as it has been found by FedDOT to be less toxic to personnel. As all asphalt characteristics were to be compared to those of the binder extracted from the unaged mix, any effect on binder character would be common to all tests and would disappear during comparisons. The solution of solvent and asphalt from the extraction process was then distilled in accordance with the Abson recovery method, ASTM D-1856.

## IX. Evaluation Procedure

The effect of aging was evaluated by measuring the penetration and the viscosity of the asphalt recovered from the mixture. In addition, changes in the asphalt viscosity temperature susceptibility after exposure to the laboratory aging were also examined.

The penetration test is an empirical measure of asphalt consistency under a given set of conditions (ASTM D-5). The test results are expressed as a distance, in tenths of a millimeter, that a standard needle penetrates vertically into an asphalt sample under known conditions of loading, time, and temperature. For this study, the standard penetration test was performed in which a load of 100 grams was applied for 5 seconds at a temperature of 77° F [17].

The penetration test results are used to calculate the Percent Penetration Retained (PPR). This parameter is defined as the ratio of the asphalt penetration after aging to that before aging.

$$PPR = \frac{\text{Penetration After Aging}}{\text{Penetration Before Aging}} \times 100\ \%$$

The viscosity of the asphalt extracted from the mixture was measured using the cone-plate viscometer following the procedure outlined in the ASTM D-3205 standard test method using gradually-increasing loads as described in Alternate No. 1 [17,18]. This method was selected because: a) it is capable of covering the widest possible shear rate range; and, b) only a small amount of asphalt is required for the test.

Viscosity at any given temperature and shear rate is defined as the ratio of shear stress to shear rate. At higher temperatures, such as 275° F, asphalts behave as simple Newtonian liquids when subjected to ordinary shear rates; that is, the ratio of shear stress to shear rate is constant. On the other hand, at low temperatures, the flow properties of the asphalt become more complex and asphalts tend to behave as non-Newtonian materials; in other words, the ratio of shear stress to shear rate is not constant.

In this study, the viscosities of asphalts were measured at three different temperatures, 32° F, 77° F, and 140° F, because these temperatures are considered as representative of the pavement temperatures in the field. The viscosities at low temperatures (32° F) were measured directly on the samples since it was undesirable to predict these values using high or moderate temperature measurements due to the difference in asphalt behavior that occurs in these temperatures.

The viscosity value when measured using a value of shear stress associated with an arbitrarily-selected shear rate is termed the apparent viscosity. At relatively low shear stress, inducing low shear rate, apparent viscosities appear to be constant. Such a constant, relatively shear independent, viscosity is designated as the initial viscosity [19]. For all viscosity measurements in this study, attempts were made to obtain the initial viscosities.

The relative aging rate of the sample was then evaluated by computing the viscosity aging index (AI). This index was defined as the ratio of the viscosity of the asphalt after to that before the laboratory aging.

$$AI = \frac{\text{Viscosity After Aging}}{\text{Viscosity Before Aging}}$$

The viscosity temperature susceptibility (VTS) of asphalt is the rate at which the viscosity of the asphalt changes with a change in temperature. To calculate the VTS within a given range of temperatures, a double logarithm of viscosity in centistokes is plotted against the logarithm of the absolute temperatures in degrees Kelvin where the measurements are taken. Such a plot generally results in a straight line, with the slope of line being equal to VTS.

$$VTS = \frac{\text{loglog viscosity at } T_2 - \text{log log viscosity at } T_1}{\log T_1 - \log T_2}$$

The VTS was calculated for a temperature range of 32° F to 140° F. A large value of VTS indicates a pronounced viscosity change with changing temperature.

Statistical analysis were used to evaluate the data. The Statistical Analysis System (SAS) computer program was utilized to generate statistics for data analyses. In all cases, a level of significance of 0.05 was used [20,21].

## X. Results and Discussion

The penetration test results are presented in table 6. The percent penetration retained (PPR) is calculated as the ratio of the asphalt penetration after aging to that before aging. The PPR values of the aged asphalt are reported in table 7. The results show that the PPR decreases with an increase in air void.

The results are tested to see if the mean of PPR is the same for all the air void levels and for the four types of mixtures. The linear model used is:

$$Y_{ij} = \mu + \beta_i + \tau_j + \epsilon_{ij}$$

where:

$Y_{ij}$ = PPR for the i-th mixture and j-th air void level;
$\mu$ = general or mean effect;
$\beta_i$ = effect due to the i-th mixture;
$\tau_j$ = effect due to the j-th air void level; and,
$\epsilon_{ij}$ = random error.

Table 6. Penetration Test Results

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 26 | 27 | 20 | 23 |
| 6 | 25 | 26 | 21 | 23 |
| 7 | 26 | 25 | 20 | 22 |
| 8 | 25 | 25 | 21 | 23 |
| 9 | 22 | 24 | 19 | 23 |
| 10 | 21 | 25 | 19 | 23 |
| 11 | 21 | 24 | 18 | 23 |
| 12 | 21 | 24 | 20 | 22 |
| 13 | 21 | 22 | 17 | 21 |
| 14 | 20 | 21 | 18 | 20 |
| 15 | 20 | 20 | 15 | 20 |

Table 7. Percent Penetration Retained (PPR)

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 93 | 100 | 87 | 96 |
| 6 | 89 | 96 | 91 | 96 |
| 7 | 93 | 93 | 87 | 92 |
| 8 | 89 | 93 | 91 | 96 |
| 9 | 79 | 89 | 83 | 96 |
| 10 | 75 | 93 | 83 | 96 |
| 11 | 75 | 93 | 78 | 96 |
| 12 | 75 | 89 | 87 | 92 |
| 13 | 75 | 81 | 74 | 88 |
| 14 | 71 | 78 | 78 | 83 |
| 15 | 71 | 74 | 65 | 83 |

Analysis of variance (ANOVA) was performed on the PPR data. The results, presented in table 8, indicate that the effects of mixture type and air void content are both significant.

Table 8. Analysis of Variance for Dependent Variable PPR

| Source | df | Sum of Squares | Mean Square | F-value | p-value |
|---|---|---|---|---|---|
| Mixture | 3 | 1017.91 | 339.30 | 21.68 | 0.0001 |
| Void | 10 | 1832.41 | 183.24 | 11.71 | 0.0001 |
| Error | 30 | 469.59 | 15.65 | | |
| Total | 40 | 3319.91 | | | |

Figure 6 is a plot of PPR against the air void content. It is shown that both class 1 mixtures (A and C) have retained less penetration and could be assumed to have aged more than the class 2 mixtures (B and D). At low air void levels (less than 9%), however, the PPR values of all mixtures are not significantly different. For the air void range of 9% to 13%, the PPR values for mixtures A and C (class 1) are significantly less than those of mixtures B and D (class 2). Above 13%, the PPR values for all mixtures are again comparable.

A simultaneous mean comparison was performed using the Student's Newman-Keul (SNK) test procedure. The results are given in table 9. It is found that the class 1 mixtures (A and C) have significantly aged more. In addition, there is no significant difference in the aging of mixtures with the same class. For example, as shown in table 9, both mixtures A and C fall in the same SNK grouping, meaning that no significant difference in the aging of mixtures A and C.

Table 9. SNK Test for Means of PPR by Mixture Type

| Mixture | Mean | N | SNK Grouping |
|---|---|---|---|
| A | 92.182 | 11 | K |
| B | 89.000 | 11 | K |
| C | 82.182 | 11 | L |
| D | 80.455 | 11 | L |

Note : Means with the same letter in the SNK grouping are not significantly different.

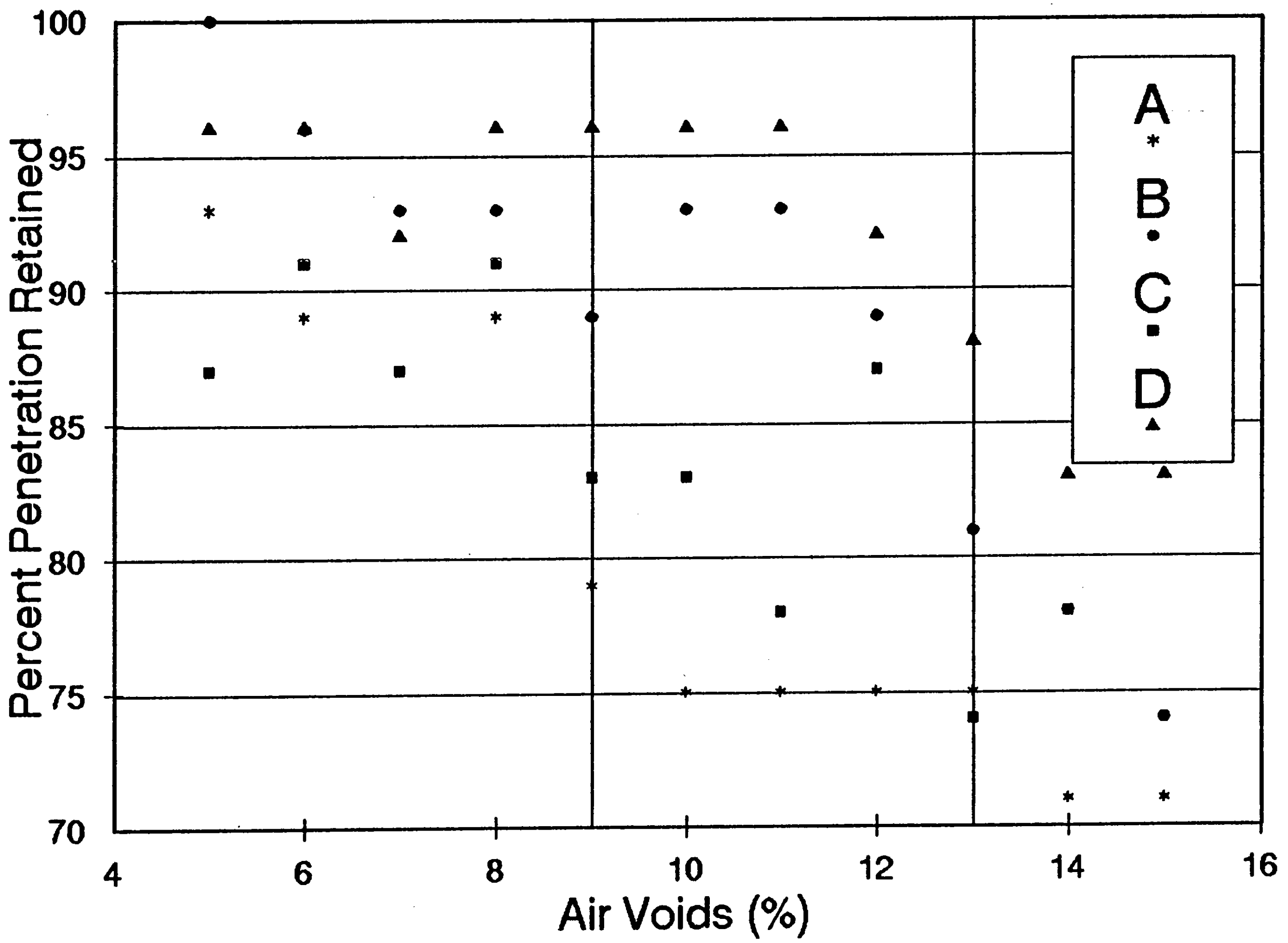


Figure 6. PPR versus Air Void

Further, it was found that the air void contents of 9% to 13% are critical for the aging to occur since the PPR values of the samples with air voids more than 13% are significantly smaller than those with air void contents less than 9% (see table 10). A plausible explanation is that below 9% voids, only little air could pass through the samples, and the aging produced was mostly due to heat. Between 9% and 13%, air flow began to establish and the aging process accelerated. Above 13%, air flowed freely and the aging took place at greater rates.

Table 10. SNK Test for Means of PPR by Air Void Level

| Void Level (%) | Mean | N | SNK Grouping |
|---|---|---|---|
| 5 | 94.00 | 4 | K |
| 6 | 93.00 | 4 | K |
| 7 | 92.25 | 4 | K |
| 8 | 91.25 | 4 | K |
| 9 | 86.75 | 4 | K L |
| 10 | 86.75 | 4 | K L |
| 12 | 85.75 | 4 | K L |
| 11 | 85.50 | 4 | K L |
| 13 | 79.50 | 4 | L M |
| 14 | 77.50 | 4 | M |
| 15 | 73.25 | 4 | M |

Note : Means with the same letter in the SNK grouping are not significantly different.

The results of viscosity tests performed at 32° F, 77° F, and 140° F are presented in tables 11, 12, and 13, respectively. As can be expected, the viscosity of the aged asphalt increases with the air void content implying that samples with higher air void contents have aged more.

The viscosity of the aged asphalt were then plotted against the air void levels. The plots show that there is a critical air void range above which viscosity changes take place more rapidly, as indicated by the change in the slope of the curve. For all temperatures at which the viscosities were taken, such a critical range is between 8% and 12%.

Figures 7, 8, 9, and 10 show the plots of viscosities measured at 32° F versus the air void content. For mixtures A and B, the break points are found at the void levels of 11%. For mixture C, viscosity changes more rapidly at air void contents between 8% and 10%. Above the 10%, with an exception for the sample with void content of 13%, the viscosity does not change much. The break point for mixture D is at the void content of 10%.

Table 11. Viscosities Measured at 32° F (in Giga-poises)

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 5.04 | 6.67 | 11.20 | 9.09 |
| 6 | 6.17 | 6.55 | 11.60 | 14.05 |
| 7 | 6.13 | 7.37 | 12.35 | 14.15 |
| 8 | 7.28 | 8.23 | 12.65 | 15.00 |
| 9 | 8.31 | 10.05 | 14.85 | 17.00 |
| 10 | 12.05 | 13.45 | 16.50 | 15.65 |
| 11 | 11.85 | 13.10 | 16.45 | 19.10 |
| 12 | 11.60 | 19.45 | 16.65 | 18.85 |
| 13 | 13.95 | 13.90 | 20.50 | 19.90 |
| 14 | 15.35 | 19.10 | 16.95 | 21.30 |
| 15 | 15.90 | 26.10 | 17.10 | 24.75 |

The plots of viscosities measured at 77° F against the air void are depicted in figures 11, 12, 13, and 14. The plots indicate that the critical voids for mixtures A, B, C, and D are 12%, 9%, 10%, and 11%, respectively.

Similar plots were also made for viscosities measured at 140° F and are shown in figures 15, 16, 17, and 18. Mixtures A, B, and D have break points at air void contents between 10% and 11%. The viscosity plot for mixture C shows a pattern similar to that measured at 32° F. The viscosity increases rapidly at void levels of 9% to 12%, but more slowly thereafter.

Table 12. Viscosities Measured at 77° F (in mega-poises)

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 37.2 | 27.8 | 103.0 | 71.5 |
| 6 | 36.1 | 28.5 | 111.0 | 76.9 |
| 7 | 40.9 | 30.2 | 112.5 | 80.6 |
| 8 | 52.9 | 36.0 | 113.5 | 85.5 |
| 9 | 51.4 | 31.8 | 126.0 | 85.3 |
| 10 | 56.3 | 38.5 | 118.0 | 101.0 |
| 11 | 60.8 | 39.1 | 192.0 | 111.0 |
| 12 | 60.0 | 48.4 | 174.0 | 99.7 |
| 13 | 68.5 | 46.7 | 170.0 | 111.0 |
| 14 | 74.4 | 49.7 | 192.0 | 119.0 |
| 15 | 88.5 | 52.2 | 237.5 | 151.0 |

Table 13. Viscosities Measured at 140° F (in kilo-poises)

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 12.00 | 6.63 | 24.50 | 22.30 |
| 6 | 13.55 | 8.63 | 28.70 | 23.80 |
| 7 | 18.05 | 11.20 | 29.80 | 24.90 |
| 8 | 26.55 | 11.45 | 34.70 | 26.00 |
| 9 | 30.35 | 11.95 | 37.00 | 26.20 |
| 10 | 33.75 | 13.30 | 42.70 | 27.70 |
| 11 | 46.05 | 13.55 | 46.00 | 31.90 |
| 12 | 55.30 | 17.60 | 50.60 | 33.70 |
| 13 | 61.05 | 22.35 | 50.50 | 34.40 |
| 14 | 76.25 | 25.00 | 52.80 | 37.20 |
| 15 | 81.10 | 29.60 | 59.80 | 38.60 |

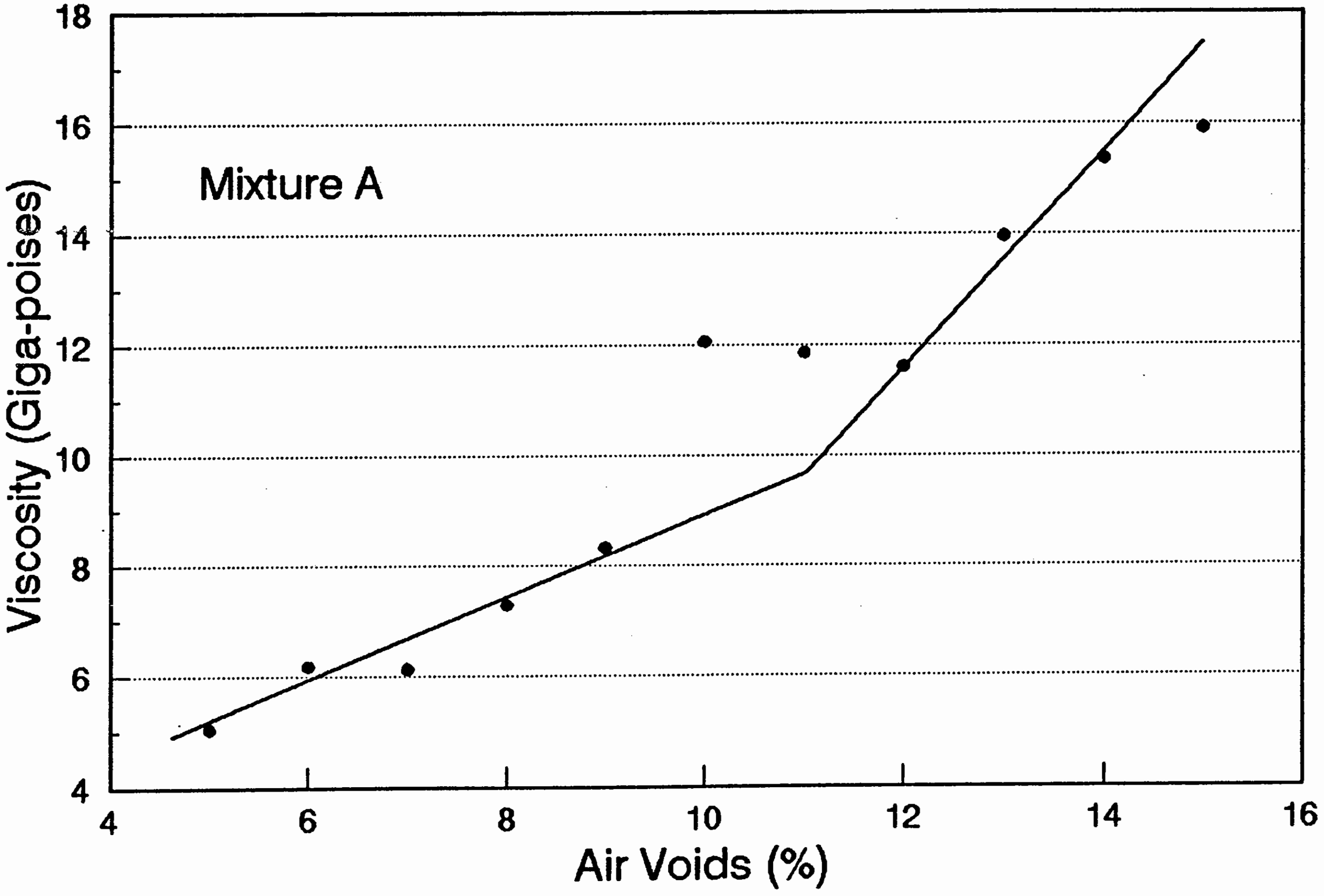


Figure 7. Viscosity at 32 F versus Air Void (Mixture A)

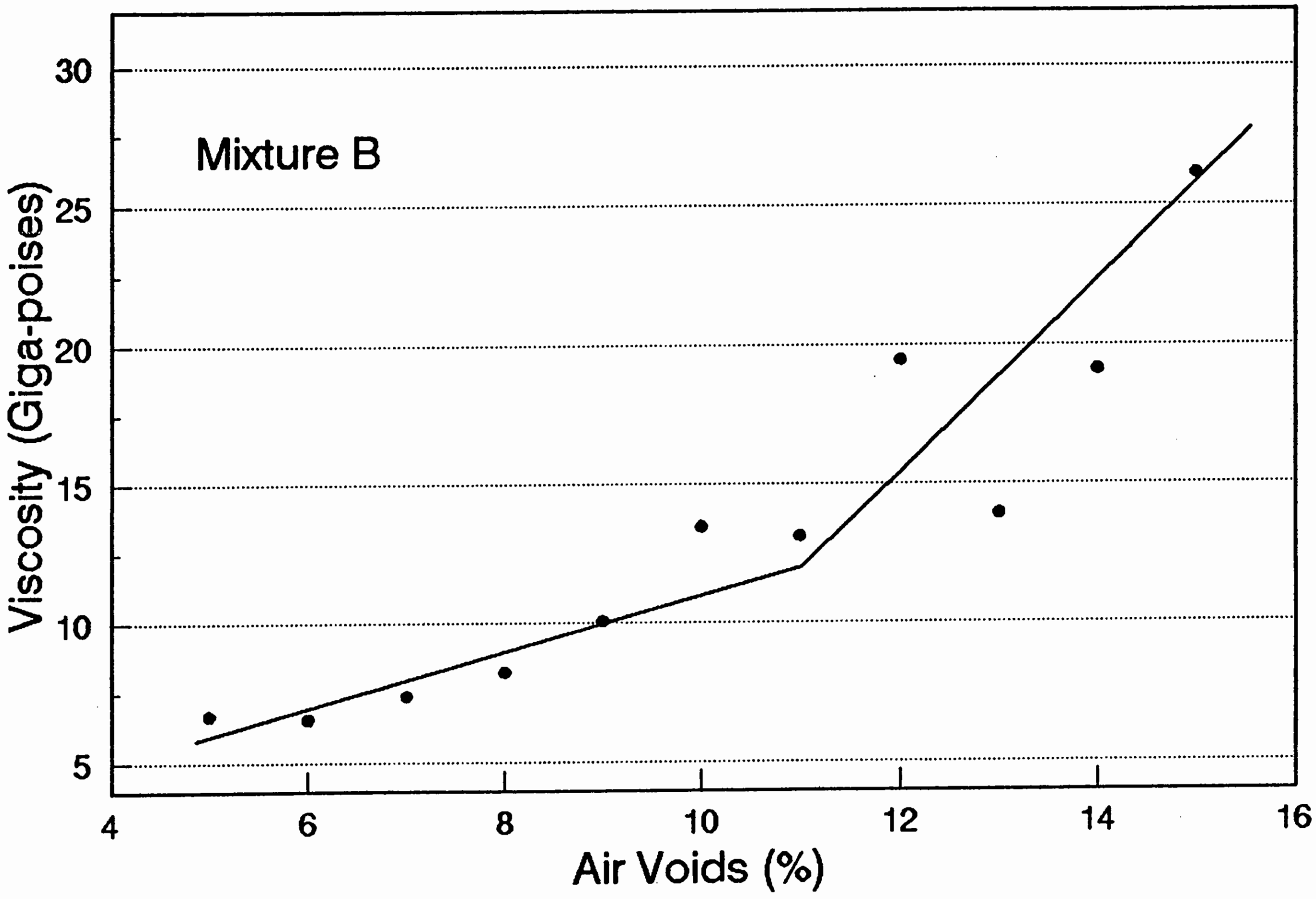


Figure 8. Viscosity at 32 F versus Air Void (Mixture B)

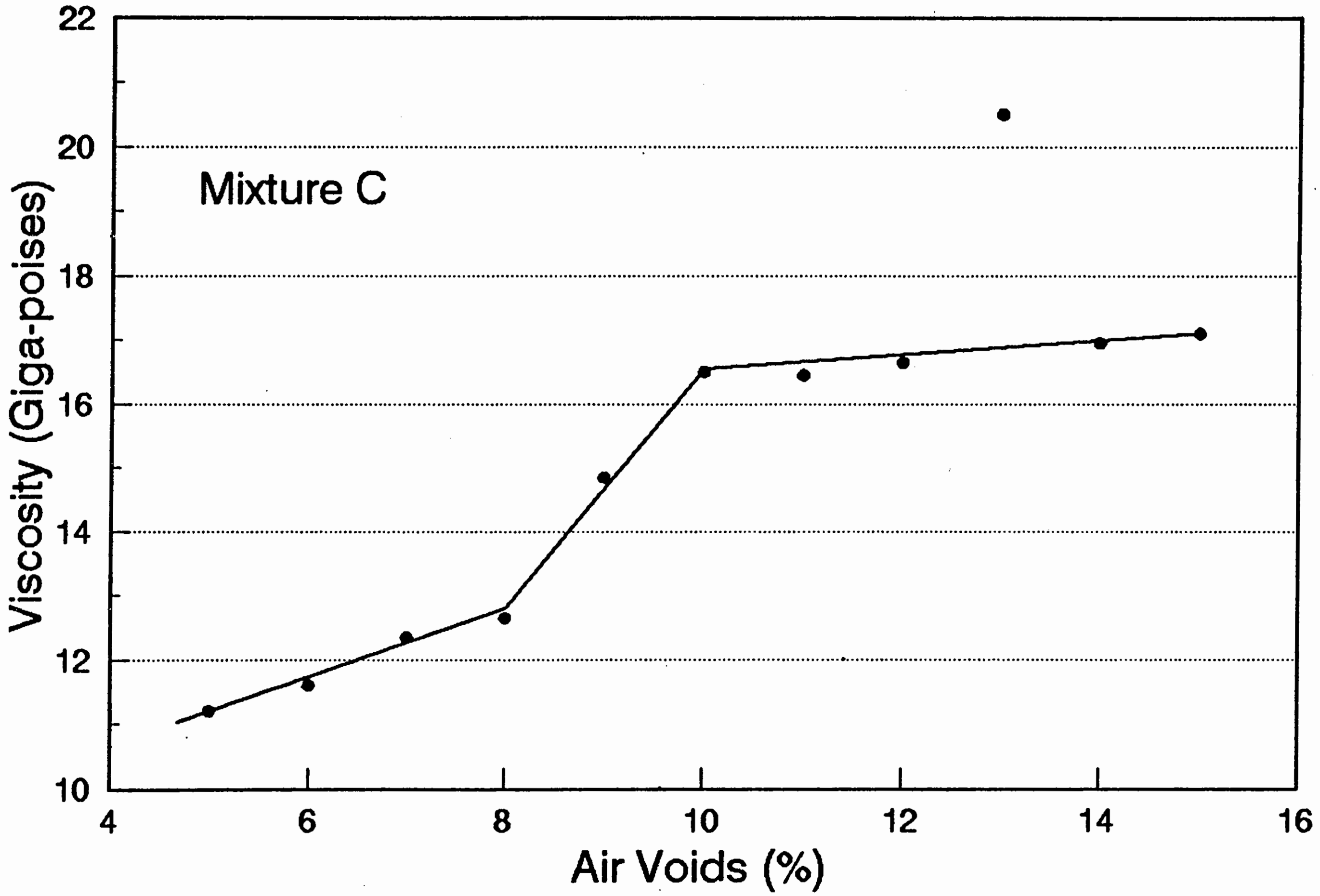


Figure 9. Viscosity at 32 F versus Air Void (Mixture C)

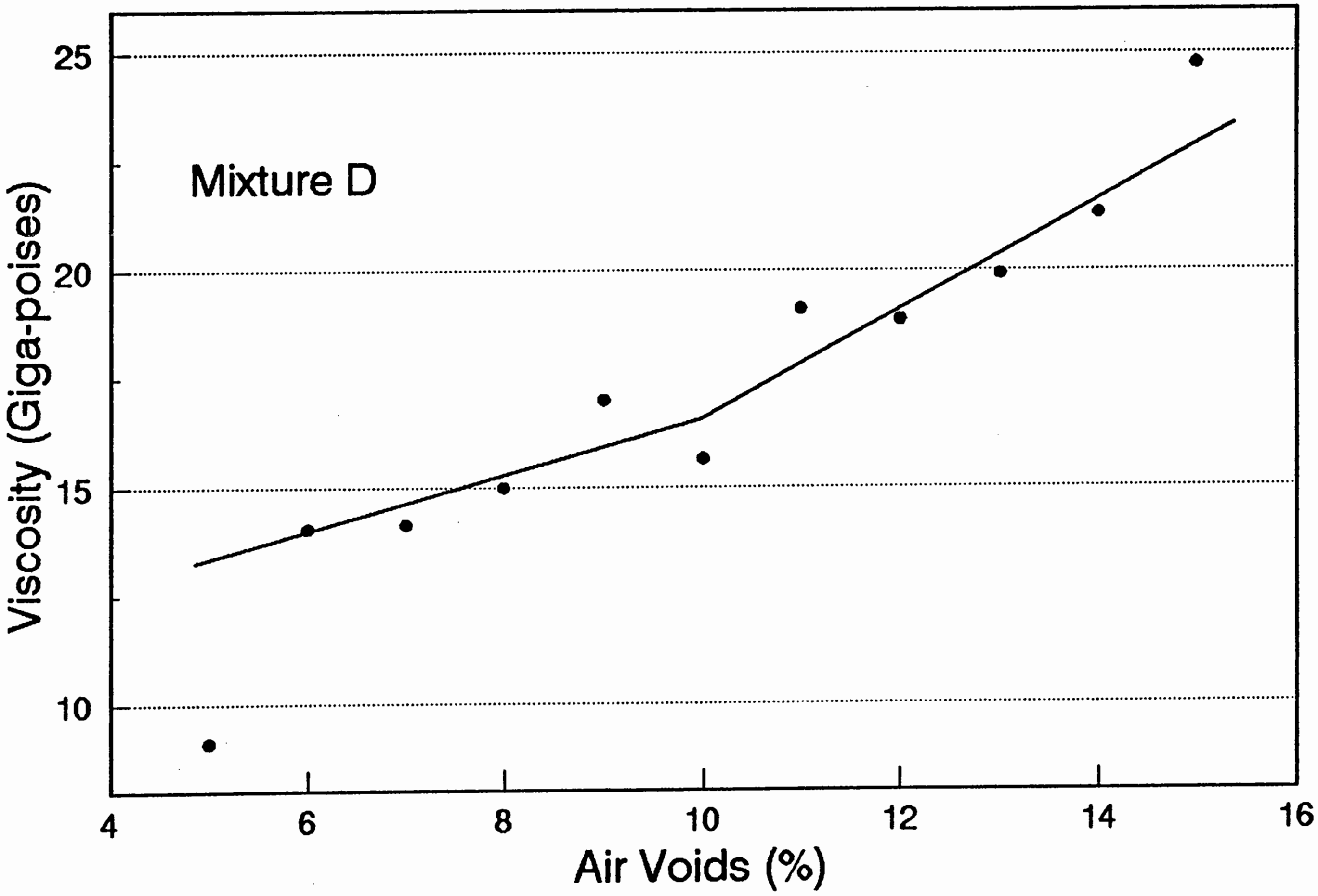


Figure 10. Viscosity at 32 F versus Air Void (Mixture D)

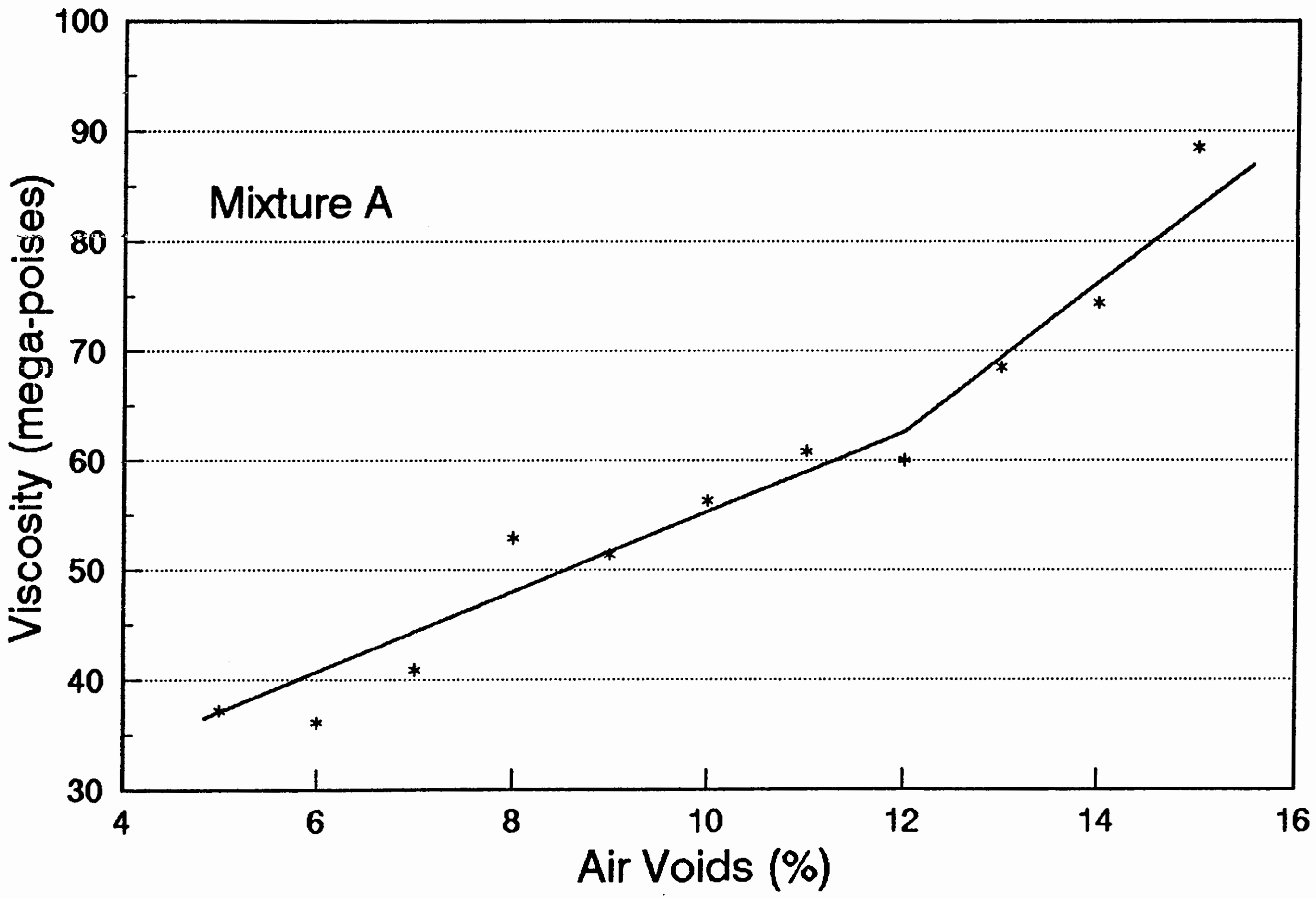


**Figure 11.** Viscosity at 77 F versus Air Void (Mixture A)

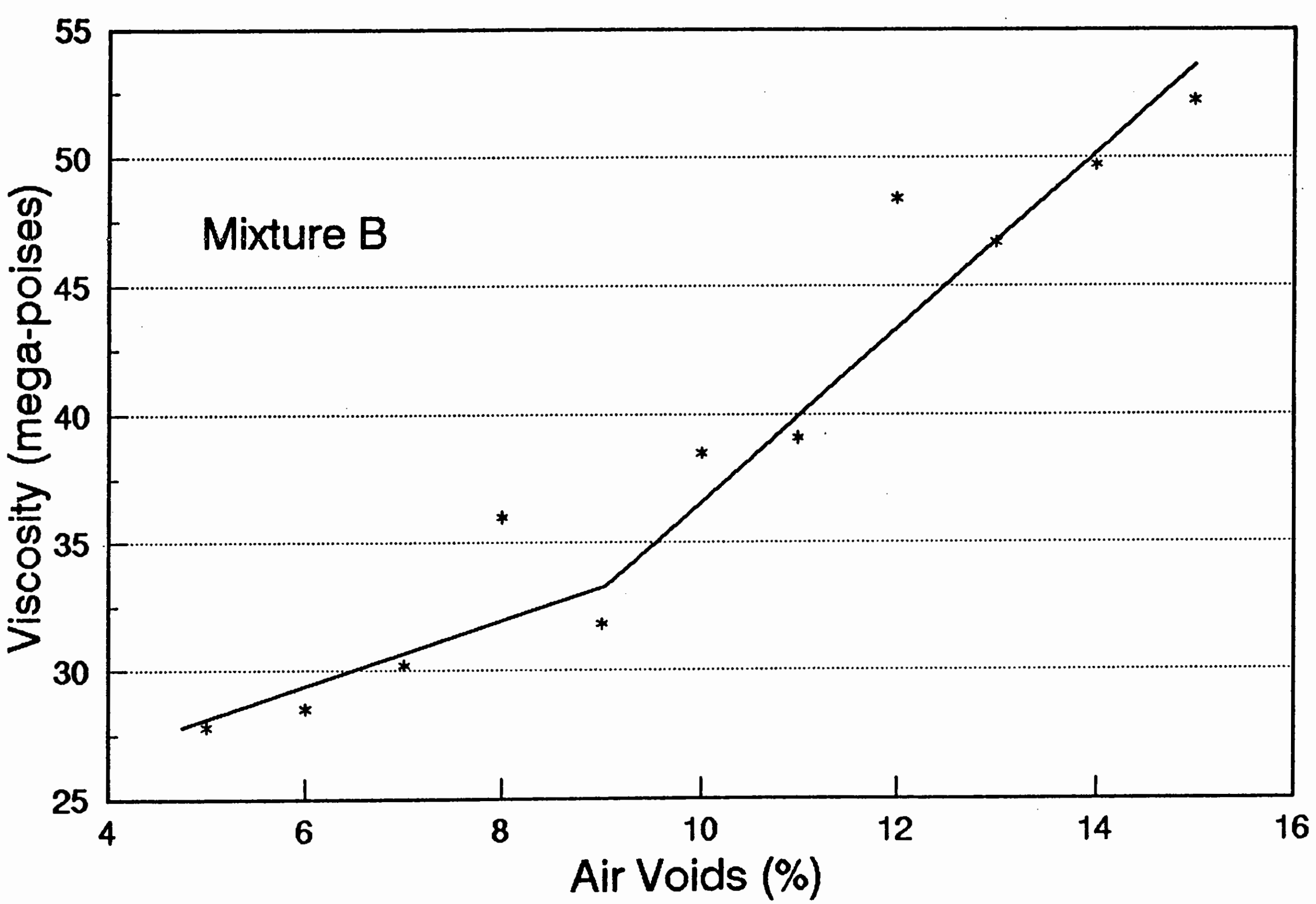


Figure 12. Viscosity at 77 F versus Air Void (Mixture B)

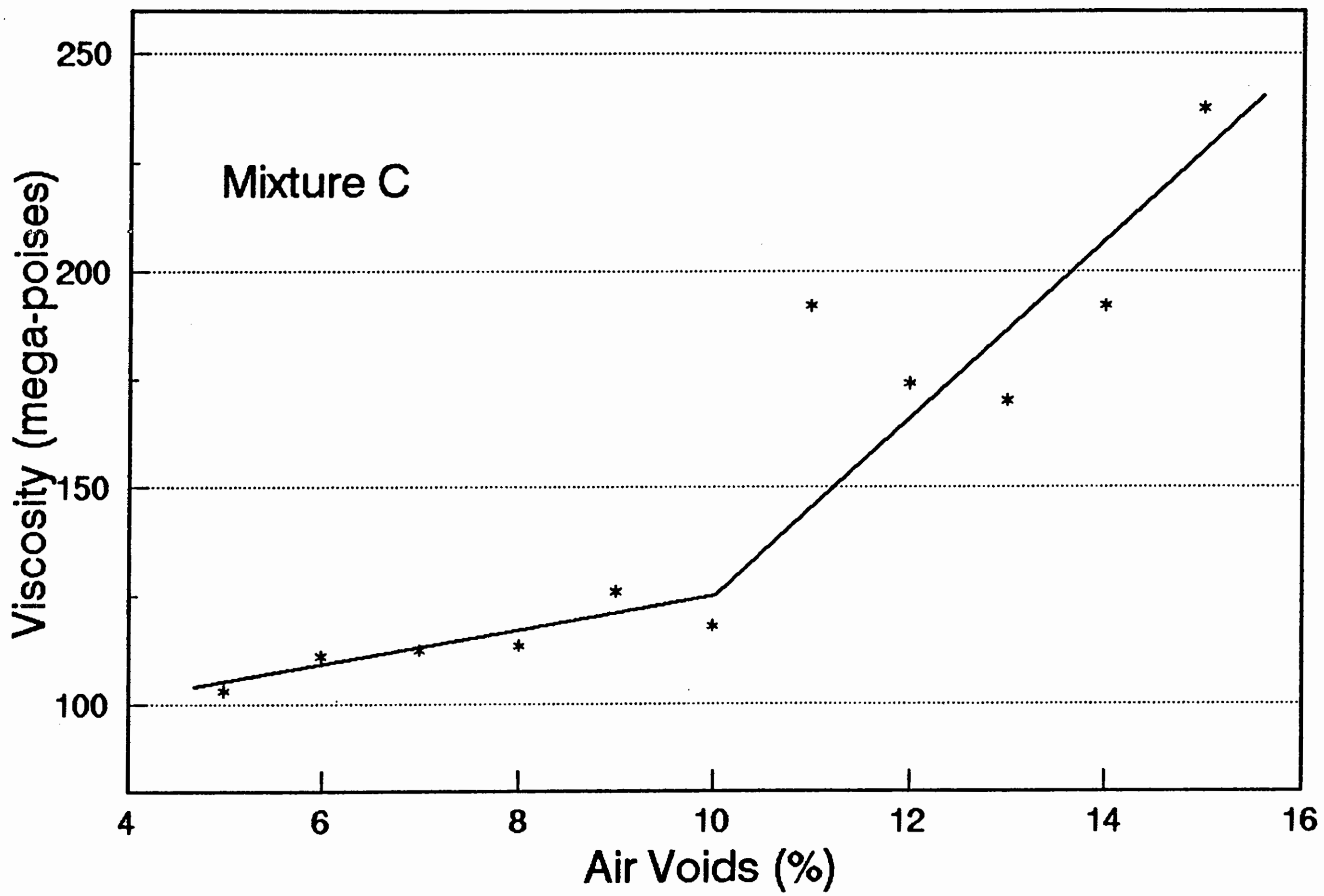


Figure 13. Viscosity at 77 F versus Air Void (Mixture C)

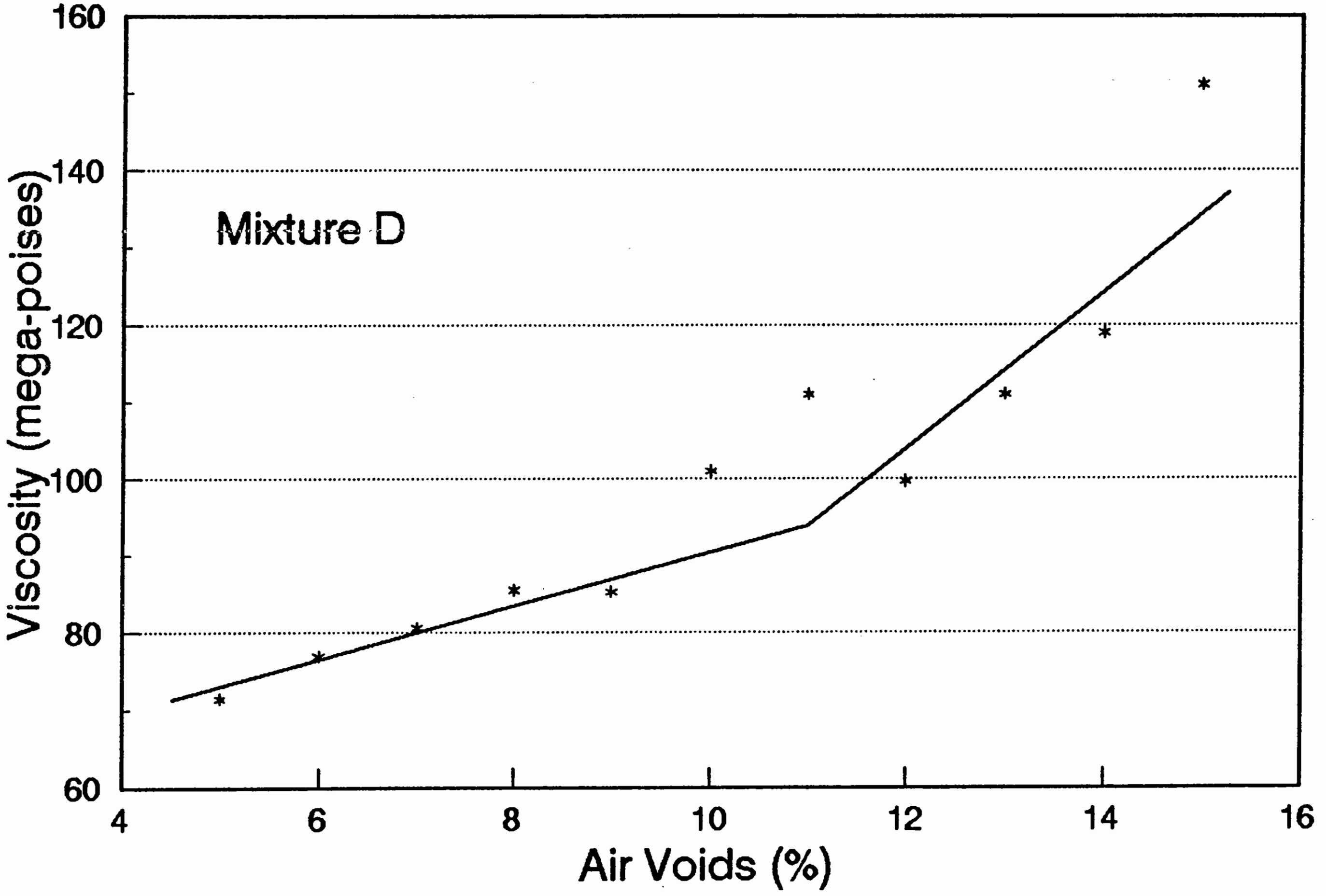


Figure 14. Viscosity at 77 F versus Air Void (Mixture D)

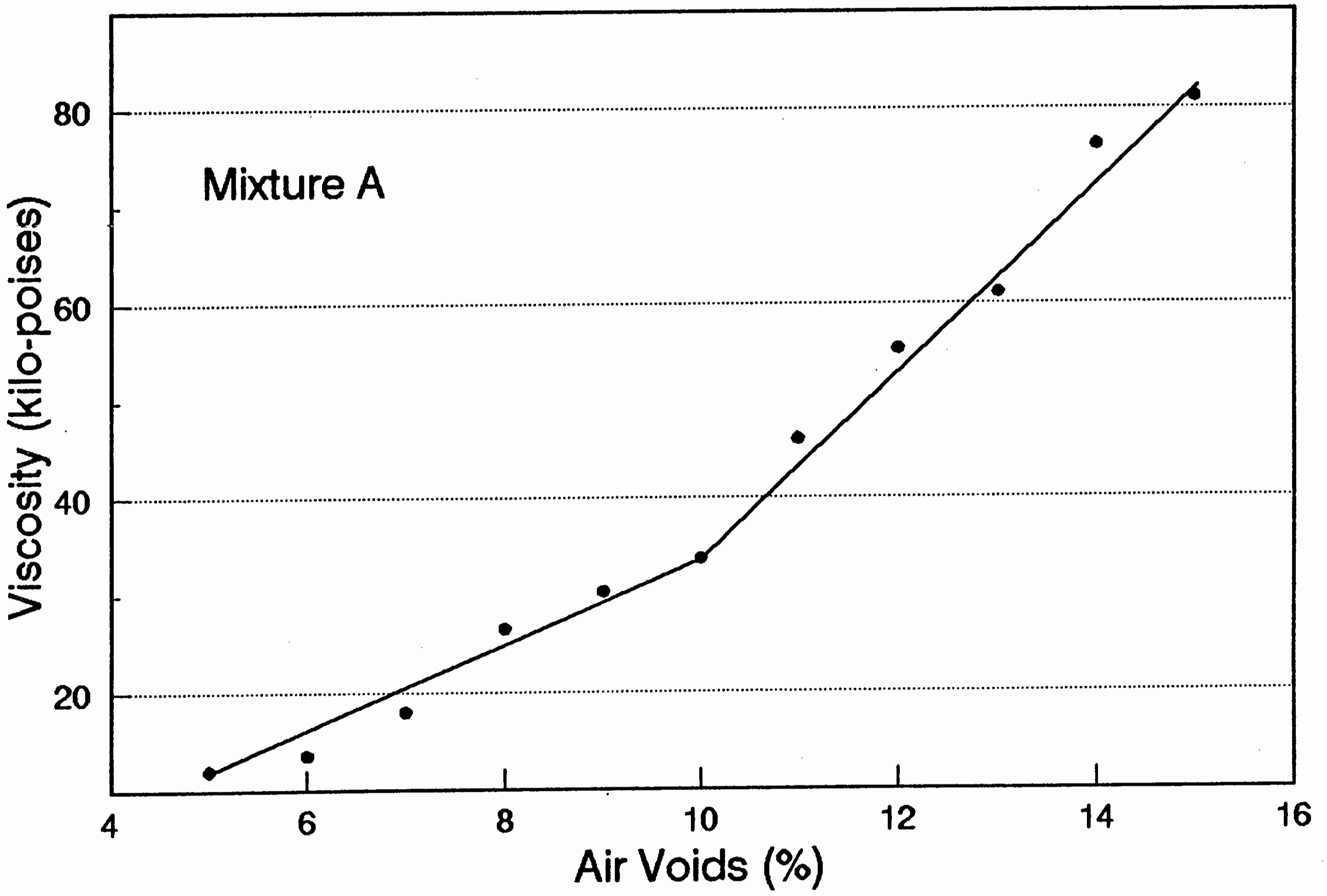


Figure 15. Viscosity at 140 F versus Air Void (Mixture A)

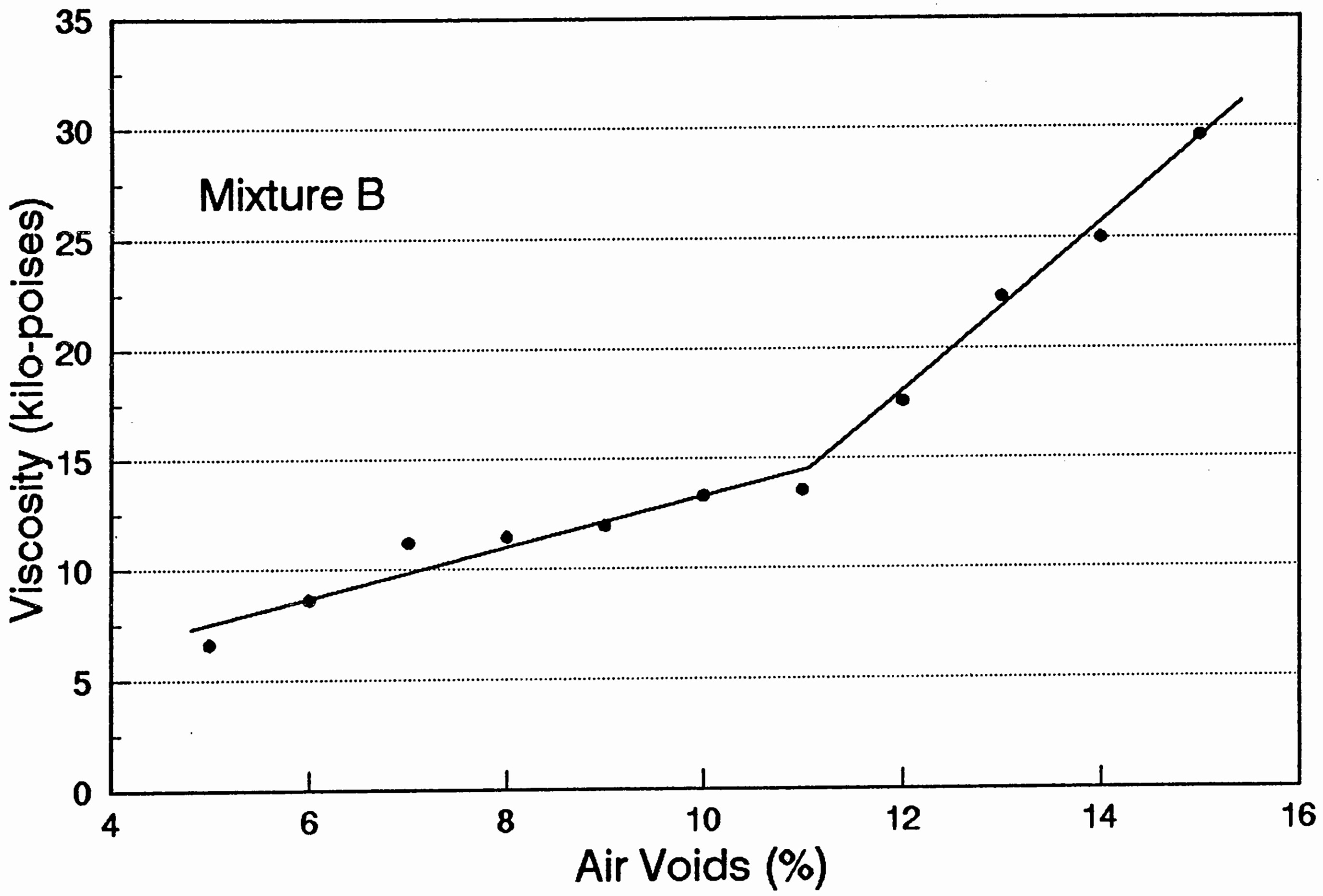


Figure 16. Viscosity at 140 F versus Air Void (Mixture B)

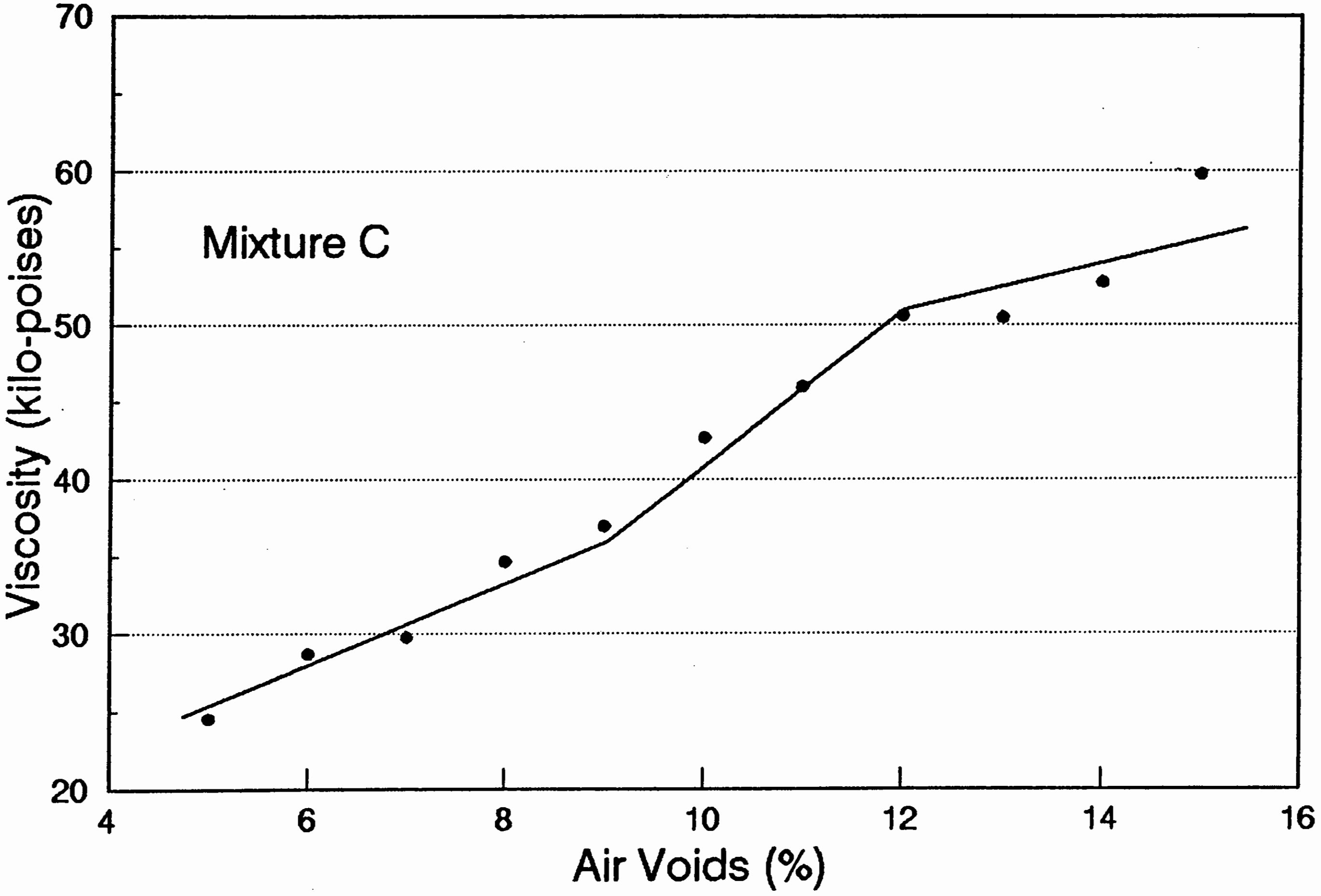


Figure 17. Viscosity at 140 F versus Air Void (Mixture C)

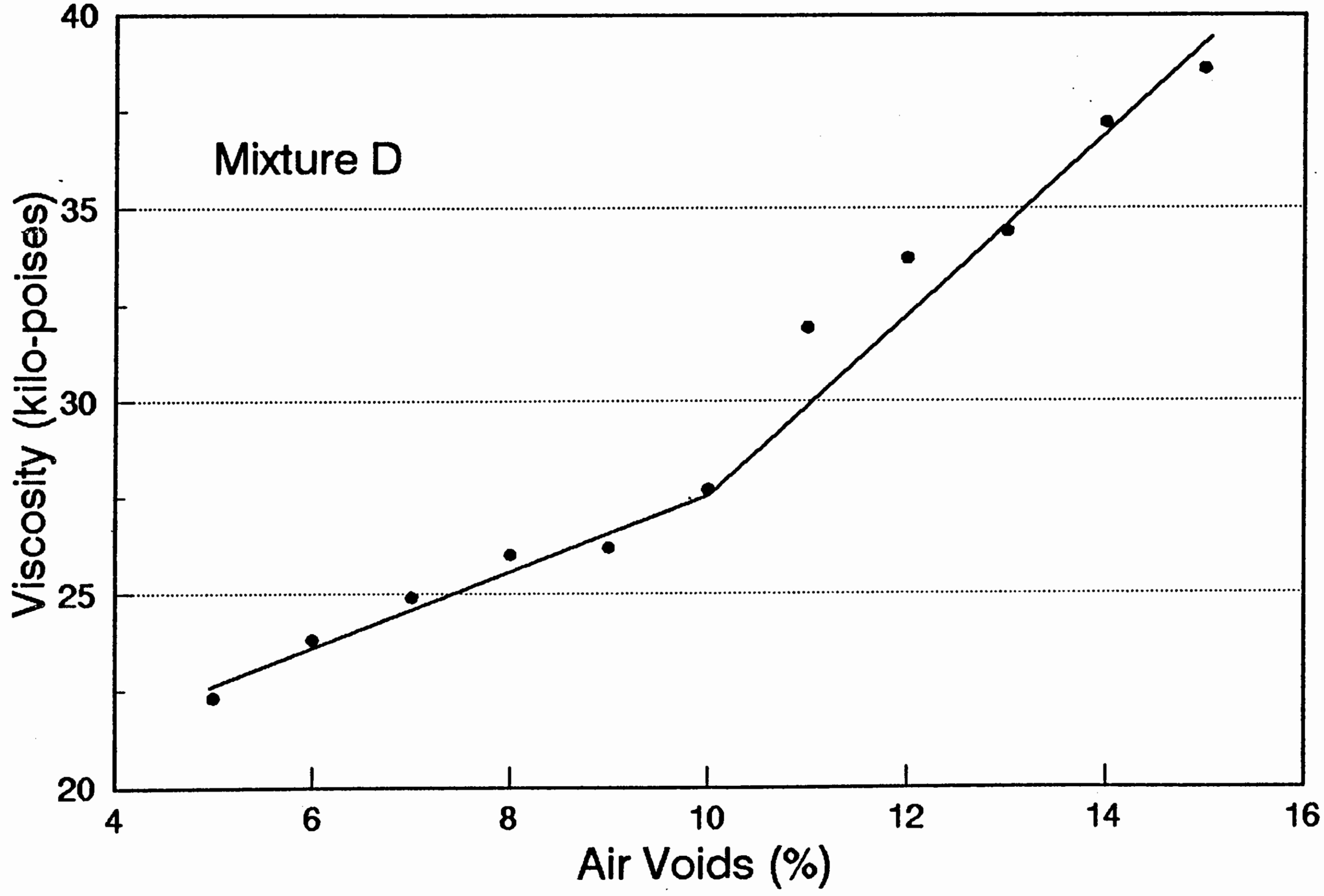


Figure 18. Viscosity at 140 F versus Air Void (Mixture D)

The relative aging rate of the sample can be evaluated by computing the viscosity aging index (AI) of the recovered asphalt. This index is defined as the ratio of the viscosity of aged asphalt to that of unaged asphalt. The aging index for the aged asphalt is presented in tables 14, 15, and 16.

To examine the effect of test temperatures, mixture types, and air void contents, the following linear model is used:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \tau_k + \epsilon_{ijk}$$

where:

$Y_{ij}$ = AI at temperature i for the j-th mixture at the k-th void level;
$\mu$ = general or mean effect;
$\alpha_i$ = effect due to test the temperature i;
$\beta_j$ = effect due to the j-th mixture;
$\tau_k$ = effect due to the k-th air void level; and,
$\epsilon_{ijk}$ = random error.

Table 14. Aging Index at 32° F

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 3.88 | 1.83 | 1.47 | 1.62 |
| 6 | 4.75 | 1.79 | 1.52 | 2.50 |
| 7 | 4.72 | 2.02 | 1.62 | 2.52 |
| 8 | 5.60 | 2.25 | 1.66 | 2.67 |
| 9 | 6.39 | 2.75 | 1.95 | 3.02 |
| 10 | 9.27 | 3.68 | 2.17 | 2.78 |
| 11 | 9.12 | 3.59 | 2.16 | 3.40 |
| 12 | 8.92 | 5.33 | 2.19 | 3.35 |
| 13 | 10.73 | 3.81 | 2.69 | 3.54 |
| 14 | 11.81 | 5.23 | 2.23 | 3.79 |
| 15 | 12.23 | 7.15 | 2.25 | 4.40 |

Table 15. Aging Index at 77° F

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 3.01 | 1.27 | 1.30 | 1.09 |
| 6 | 2.92 | 1.30 | 1.40 | 1.17 |
| 7 | 3.31 | 1.38 | 1.42 | 1.23 |
| 8 | 4.28 | 1.64 | 1.43 | 1.30 |
| 9 | 4.16 | 1.45 | 1.59 | 1.30 |
| 10 | 4.55 | 1.76 | 1.49 | 1.54 |
| 11 | 4.92 | 1.78 | 2.42 | 1.64 |
| 12 | 4.86 | 2.21 | 2.19 | 1.52 |
| 13 | 5.55 | 2.13 | 2.14 | 1.69 |
| 14 | 6.02 | 2.27 | 2.42 | 1.81 |
| 15 | 7.17 | 2.38 | 2.99 | 2.30 |

Table 16. Aging Index at 140° F

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 1.76 | 1.11 | 1.42 | 1.61 |
| 6 | 1.99 | 1.45 | 1.66 | 1.72 |
| 7 | 2.65 | 1.88 | 1.72 | 1.80 |
| 8 | 3.90 | 1.92 | 2.01 | 1.88 |
| 9 | 4.45 | 2.00 | 2.14 | 1.89 |
| 10 | 4.95 | 2.23 | 2.47 | 2.00 |
| 11 | 6.76 | 2.27 | 2.67 | 2.30 |
| 12 | 8.11 | 2.95 | 2.93 | 2.43 |
| 13 | 8.96 | 3.74 | 2.93 | 2.48 |
| 14 | 11.19 | 4.19 | 3.06 | 2.68 |
| 15 | 11.90 | 4.96 | 3.47 | 2.79 |

The analysis of variance indicates that all effects of test temperature, mixture type, and air void level are significant (see table 17). Further analysis also shows that the mean of aging index for mixture A is significantly greater than those for other mixtures, implying that mixture A has aged the most.

Table 17. Analysis of Variance for Dependent Variable AI

| Source | df | Sum of Squares | Mean Square | F-value | p-value |
|---|---|---|---|---|---|
| Mixture | 3 | 377.479 | 125.826 | 86.51 | 0.0001 |
| Temp | 2 | 63.327 | 31.664 | 21.77 | 0.0001 |
| Void | 10 | 161.930 | 16.193 | 11.13 | 0.0001 |
| Error | 116 | 168.721 | 1.455 | | |
| Total | 131 | 771.457 | | | |

Table 18. SNK Test for Means of AI by Mixture Type

| Mixture | Mean | N | SNK Grouping |
|---|---|---|---|
| A | 6.21 | 33 | K |
| B | 2.66 | 33 | L |
| C | 2.24 | 33 | L |
| D | 2.10 | 33 | L |

Note : Means with the same letter in the SNK grouping are not significantly different.

It was also found that the aging indexes varied with the temperature at which the viscosity tests were taken. The AI measured at 32° F is the highest followed by those measured at 140° F and 77° F, respectively. This result suggests that aging evaluation based on the viscosity aging index at one temperature could be misleading because a large change in viscosity at one temperature is not necessarily indicative of large changes at other temperatures. Another interpretation of this is that viscosity measured at 32° F was affected more by the laboratory aging than those measured at 77° F and 140° F.

The range of aging indexes also tends to increase with air void content. For example, for AI measured at 140° F with air void content of 5%, the range was 1.11 to 1.76 (see table 16). At 15% void, however, this range lies between 2.79 and 11.90. This indicates that asphalts with similar aging indexes at low void levels can differ substantially at high voids.

Using the SNK method, it was shown that the critical voids for the samples fall between 9% and 11% (see table 20). The relative aging rates of the samples with void levels of 12% and above are significantly higher than those of samples with air void contents of 8% and less. Since the aging condition was identical for all samples, the difference in the aging rate should be caused by the difference in the air void contents in the samples.

Table 19. SNK Test for Means of AI by Test Temperature

| Temperature | N | Mean | SNK Grouping |
|---|---|---|---|
| 32° F | 44 | 4.14 | K |
| 140° F | 44 | 3.30 | L |
| 77° F | 44 | 2.45 | M |

Note : Means with the same letter in the SNK grouping are not significantly different

Table 20. SNK Test for means of AI by Air Void Level

| Void Level (%) | Mean | N | SNK Grouping |
|---|---|---|---|
| 15 | 5.33 | 12 | K |
| 14 | 4.73 | 12 | K L |
| 13 | 4.20 | 12 | K L M |
| 12 | 3.92 | 12 | L M N |
| 11 | 3.59 | 12 | L M N O |
| 10 | 3.24 | 12 | M N O P |
| 9 | 2.76 | 12 | N O P Q |
| 8 | 2.55 | 12 | O P Q |
| 7 | 2.19 | 12 | P Q |
| 6 | 2.01 | 12 | P Q |
| 5 | 1.78 | 12 | Q |

Note : Means with the same letter in the SNK grouping are not significantly different.

The viscosity aging indexes measured at 32° F, 77° F, and 140° F were plotted against air voids in figures 19, 20, and 21, respectively. For all temperatures, the AI of mixture A is significantly higher than the others, indicating that mixture A has aged more. It is also shown in the figures that the aging index is significantly reduced at low air void levels. Figure 21 also shows that the difference in AI for the mixture types becomes less distinct for samples with low air voids.

The results explained in the previous paragraphs are summarized in table 21. It was found that the critical voids varied between mixtures and procedures used. The lowest critical voids found was 8%, for mixture C obtained by plotting viscosity versus the air voids, and the highest was 13%, for all mixtures using multiple mean comparison with PPR. Overall, a conservative value for the critical voids level is suggested as 9%.

Table 21. Critical Voids Determined by Various Procedures

| Evaluation Procedure | Mixture A | Mixture B | Mixture C | Mixture D |
|---|---|---|---|---|
| Multiple Comparison Using PPR | 9% - 13% | 9% - 13% | 9% - 13% | 9% - 13% |
| Viscosity Measured at 32° F | 11% | 11% | 8% - 10% | 10% |
| Viscosity Measured at 77° F | 12% | 9% | 10% | 11% |
| Viscosity Measured at 140° F | 10% | 11% | 9% - 12% | 10% |
| Multiple Comparison Using AI | 9% - 11% | 9% - 11% | 9% - 11% | 9% - 11% |
| Critical Void Range | 9% - 13% | 9% - 13% | 8% - 13% | 9% - 13% |
| Suggested Critical Void | 9% | 9% | 9% | 9% |

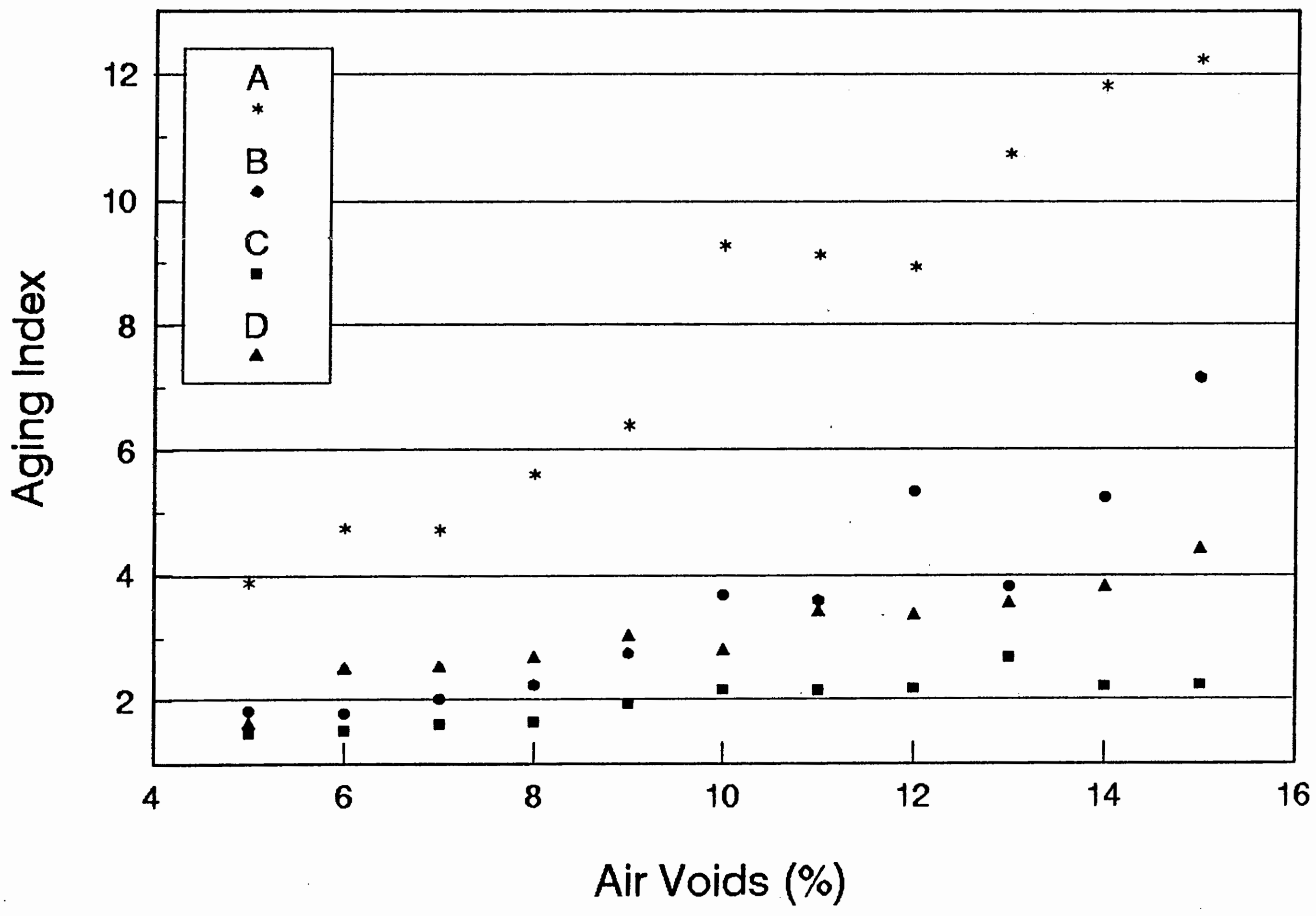


Figure 19. AI at 32 F versus Air Void

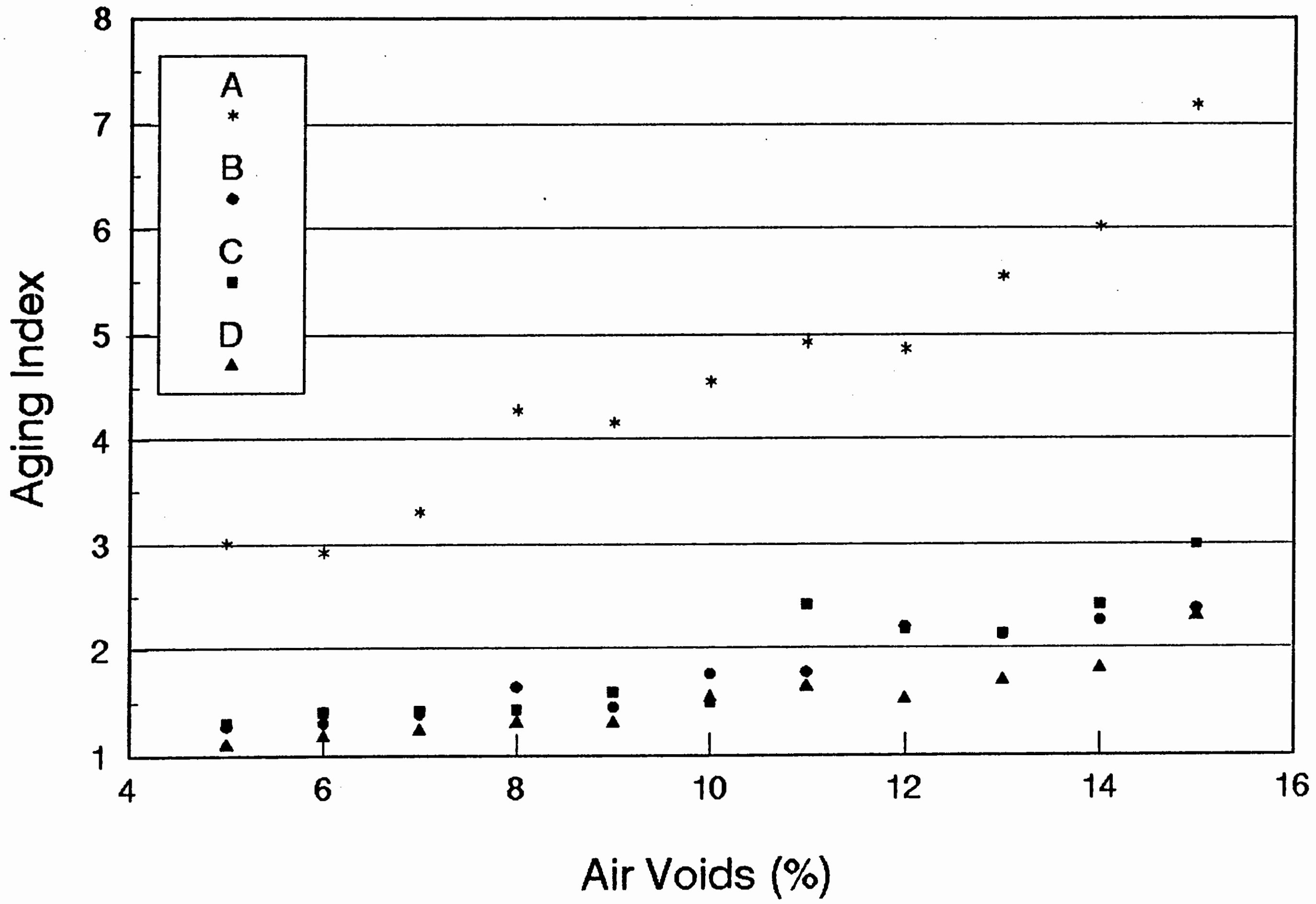


Figure 20. AI at 77 F versus Air Void

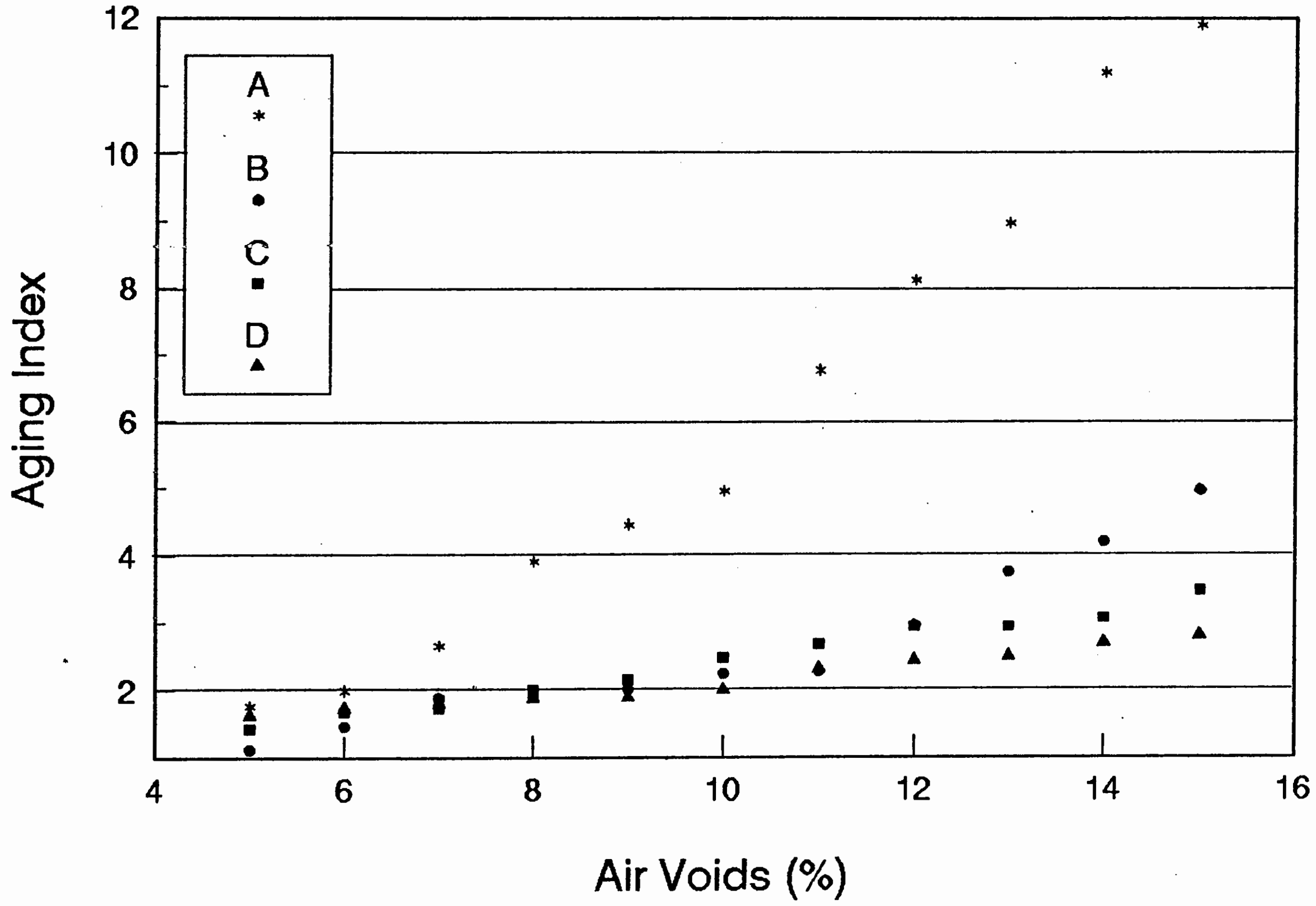


Figure 21. AI at 140 F versus Air Void

The viscosity temperature susceptibility (VTS) of the aged asphalt was determined for a temperature range of 32° F to 140° F. The results are given in table 22.

Figures 22, 23, 24, and 25 show the plots of VTS against the air void for mixtures A, B, C, and D, respectively. The plots suggest that there is a trend for VTS to decrease with air void and, hence, with the laboratory aging. However, some scatter is found in the plot of VTS and air voids for mixture B (see figure 23).

It is not clear what factor caused the VTS change. A study by Button et al (1983) shows that there is no consistency in the effect of aging on VTS. The VTS of some asphalts increases on oven aging while that of others may decrease and still others exhibit no appreciable change [22].

Table 22. VTS of the Aged Asphalt

| Air Void Content (%) | Recovered from Mixture A | Recovered from Mixture B | Recovered from Mixture C | Recovered from Mixture D |
|---|---|---|---|---|
| 5 | 3.30 | 3.57 | 3.19 | 3.19 |
| 6 | 3.29 | 3.46 | 3.15 | 3.24 |
| 7 | 3.19 | 3.39 | 3.14 | 3.23 |
| 8 | 3.09 | 3.40 | 3.10 | 3.23 |
| 9 | 3.07 | 3.43 | 3.11 | 3.25 |
| 10 | 3.10 | 3.44 | 3.08 | 3.21 |
| 11 | 2.99 | 3.43 | 3.05 | 3.20 |
| 12 | 2.93 | 3.41 | 3.02 | 3.18 |
| 13 | 2.93 | 3.26 | 3.06 | 3.18 |
| 14 | 2.88 | 3.28 | 3.01 | 3.17 |
| 15 | 2.86 | 3.28 | 2.97 | 3.18 |

For all aged asphalts recovered from each mixture, the following hypothesis test is performed :

$$H_o : VTS_{\text{after aging}} = VTS_{\text{before aging}}$$

versus

$$H_a : VTS_{\text{after aging}} < VTS_{\text{before aging}}$$

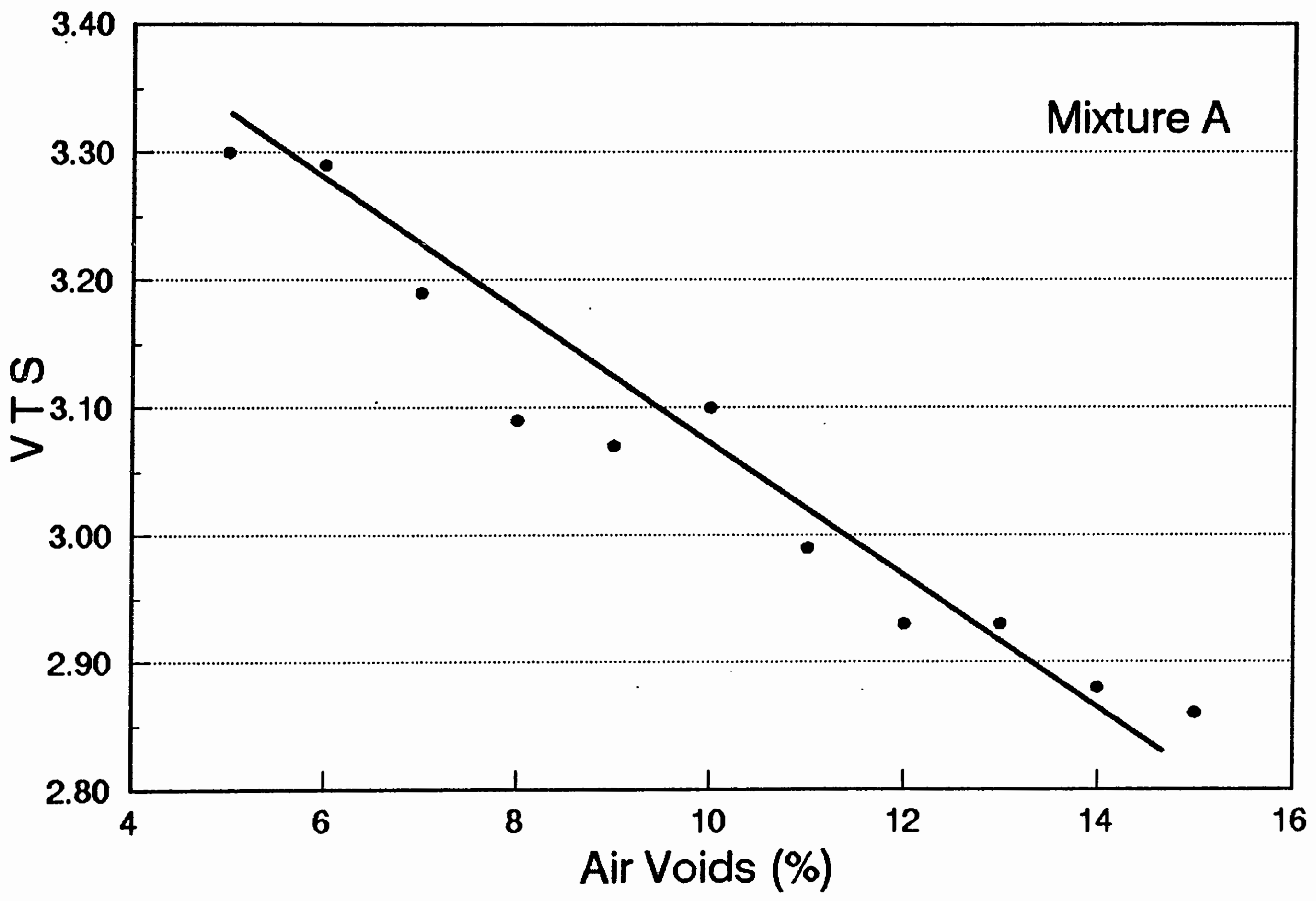


Figure 22. VTS versus Air Void (Mixture A)

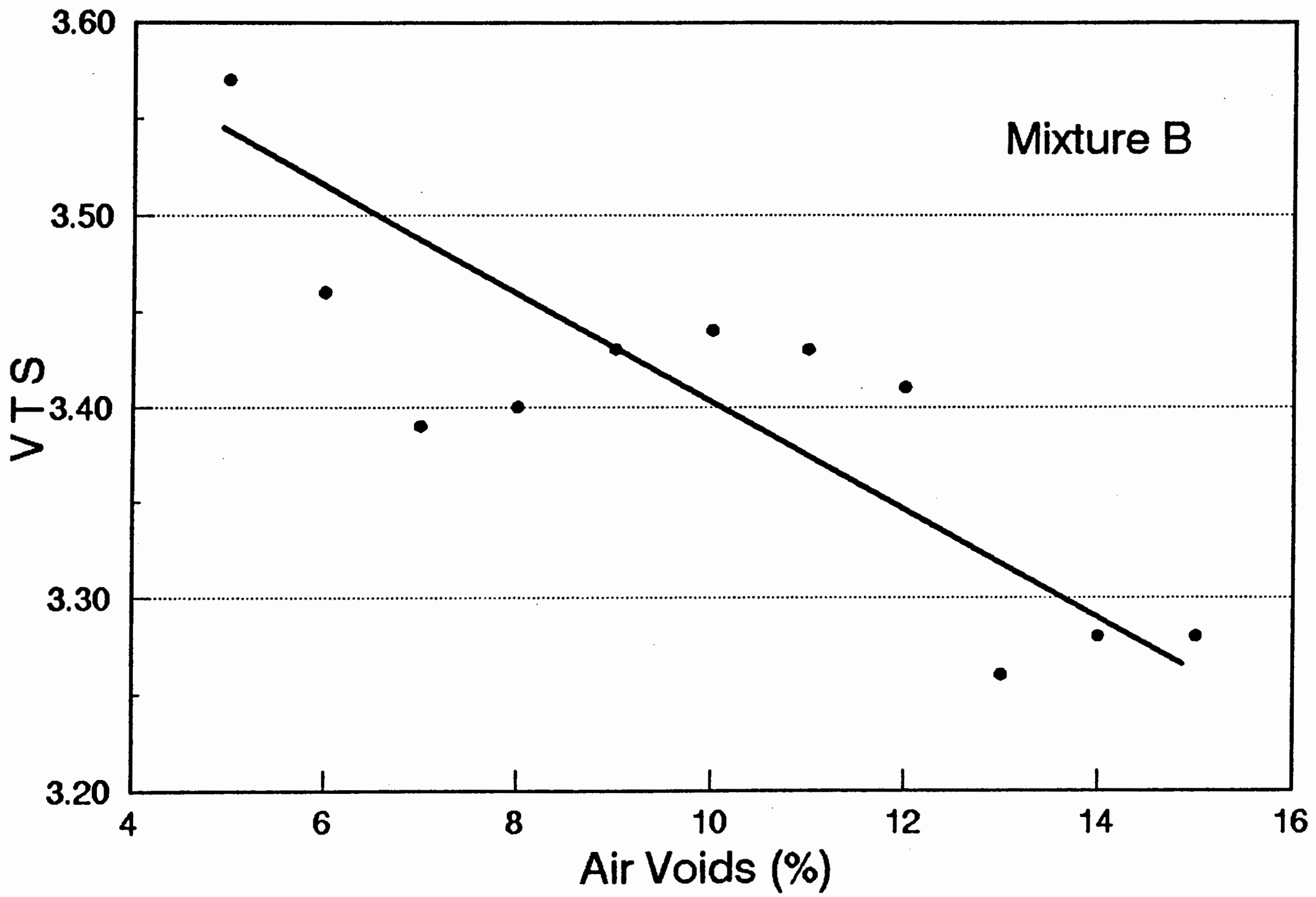


Figure 23. VTS versus Air Void (Mixture B)

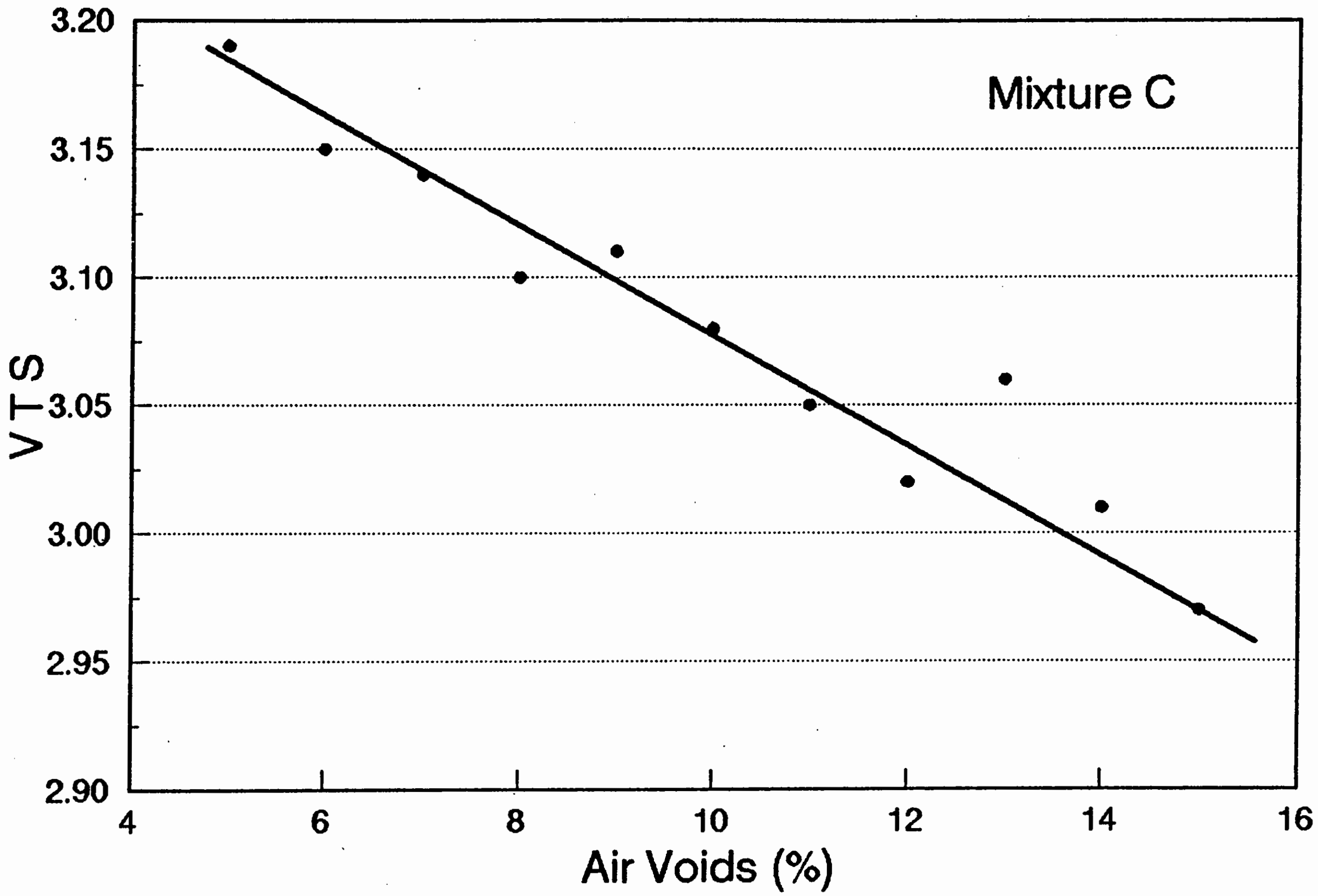


Figure 24. VTS versus Air Void (Mixture C)

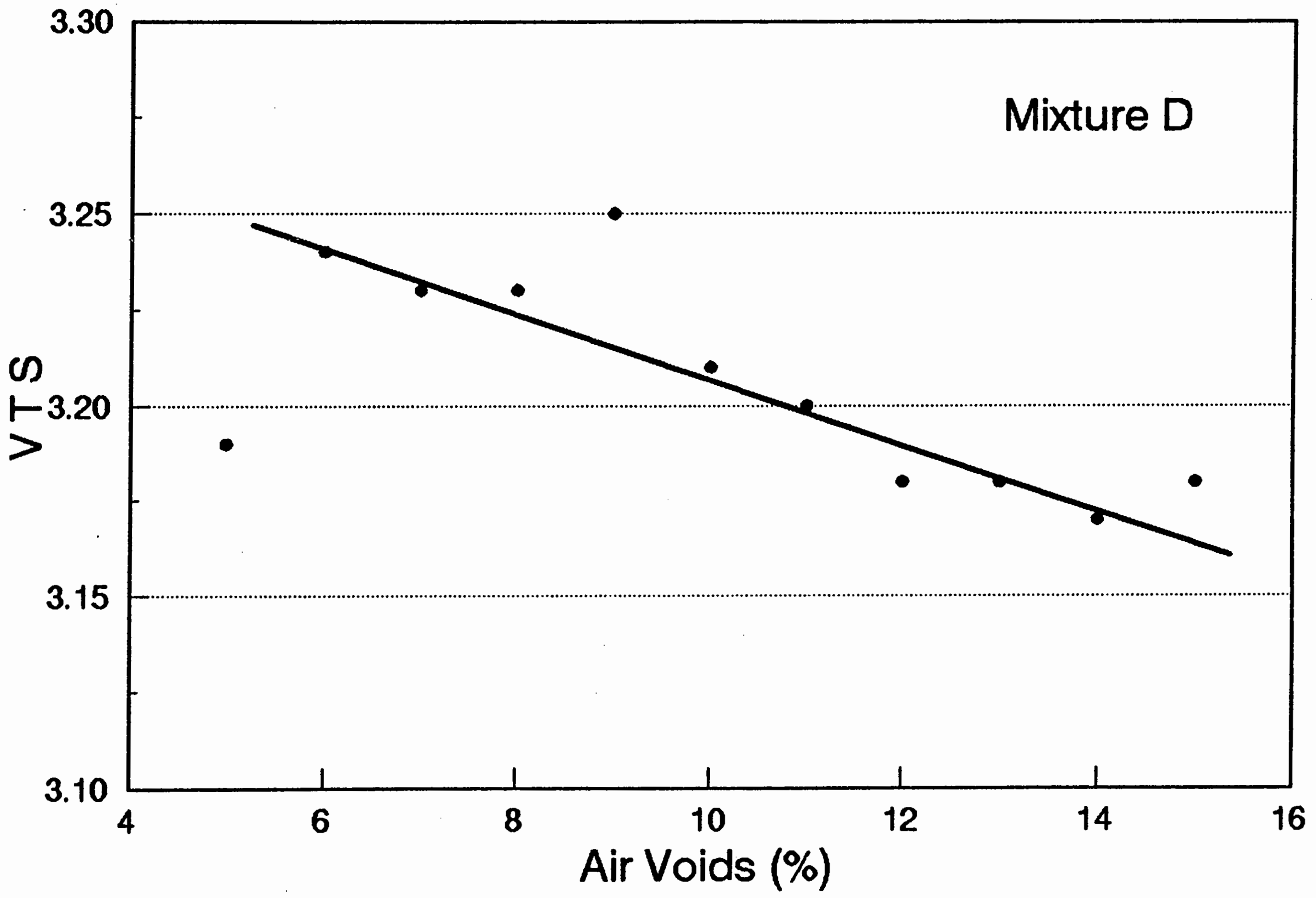


Figure 25. VTS versus Air Void (Mixture D)

A nonparametric approach was used because normality assumption for the data seems unreasonable. The test results are presented in table 23. In all cases, the $H_0$ hypotheses are rejected; thus, the VTS after aging is less than the VTS before aging.

Table 23. Nonparametric Sign Test Results

| Mixture | VTS Before Aging | Median of VTS after Aging | p-value |
|---|---|---|---|
| A | 3.24 | 3.07 | 0.0327 |
| B | 3.49 | 3.41 | 0.0059 |
| C | 4.04 | 3.08 | 0.0005 |
| D | 3.28 | 3.20 | 0.0005 |

## XI. Conclusions

A laboratory aging procedure has been performed to study the aging of asphalt mixtures. The study was intended to determine the critical asphalt pavement voids defined as the void level in the mixture above which oxidative aging occurs more rapidly.

Four types of mixtures were studied consisting of the Connecticut DOT specifications classes 1 and 2 with both round and angular aggregates. For each mixture, samples were prepared at predetermined void contents ranging from 5% to 15% using a gyratory compaction machine.

An oven aging procedure was selected in this study in which oxygen in the air was used to accelerate the aging process. The samples were placed in the oven set at 140° F for a period of 24 hours. During this period, air at a low pressure of 0.1 psi was applied to one face of the samples. Upon the completion of this process, the asphalt in the aged specimen was recovered using the Abson recovery method.

The parameters used to assess the effect of aging were the percent penetration retained (PPR) and the viscosity aging index (AI). The results show that air voids significantly affect the relative aging rate of the asphalt in the mixture. The relative aging rate increases with the air void revealing that mixtures with greater air void contents aged more.

Using the PPR, it was found that the critical pavement voids are between 9% and 13%. It was also found that, at air void contents between 9% and 13%, class 1 mixtures aged more rapidly than the class 2. Below and above this range, the PPR values for all mixtures are about the same. Overall, the PPR results indicate that the class 1 mixtures aged more than the class 2.

Using the AI, the critical voids were determined to be between 9% and 11%. The results show that mixture A (class 1 with gravel) aged more than the other mixtures.

The results provide some guidance for setting an upper limit on voids if aging is to be slowed. However, the initial voids can change due to the effect of the daily temperature cycle and compaction due to traffic. Setting the specification at 9% when compaction is completed would probably be too high as the voids in non-wheel path areas may, after a number of daily temperature cycles, be above the critical quantity. More research is needed to evaluate the rate at which voids change with time.

In the field, the critical air void content cannot be determined directly. In retrospect, permeability maybe a better control quantity as direct field determination is possible. A study toward conversion from voids to permeability should be undertaken. The critical voids content could then be used as a means of determining the need for seal coating or other treatment. Application of a treatment sooner than needed is an ineffective use of resources, but sealing too late means sealing an already aged pavement.

The gradation of the mixture is also found to be significant in determining the rate of aging. Using the PPR, it is found that the coarser grade mixture (Connecticut DOT specification class 1) was less resistant to aging.

The viscosity temperature susceptibility (VTS) of the asphalt before and after laboratory aging was also compared. It is shown that the VTS was decreased after the laboratory aging.

## XII. References

1. State of Connecticut, Department of Transportation. "BUREAU OF HIGHWAYS AND MAINTENANCE OPERATING BUDGET." Unpublished. 1990.

2. Winfrey, R. and P.D. Howell. Highway Research Record 252. HRB. Washington, D.C.

3. Malan, G.W, P.J Straus, and J. Craus. "A FIELD STUDY OF PREMATURE SURFACE CRACKING IN ASPHALT". Proceedings, AAPT. 1989.

4. Bruce and Clarkson. "HIGHWAY DESIGN AND CONSTRUCTION".

International Press. p. 443. 1950.

5. Monismith, C. "ASPHALT PAVING MIXTURES". ITTE. 1961.

6. Bell C.A. "SUMMARY REPORT ON AGING OF ASPHALT AGGREGATE SYSTEMS." National Research Council. 1989.

7. Valerga, B.A and W.J Halstead. "EFFECTS OF FIELD AGING ON FUNDAMENTAL PROPERTIES OF PAVING ASPHALTS." Highway Research Record No. 361. TRB. Washington, D.C. pp. 71-91. 1971.

8. Roberts, F.L., P.S. Kandhal, E.R. Brown, D. Lee, and T.W. Kennedy. "HOT MIX ASPHALT MATERIALS, MIXTURE DESIGN, AND CONSTRUCTION." NAPA Education Foundation. Lanham, M.D. 1991.

9. Phelps, H.E. "AN EVALUATION OF TRENDS TOWARD THE USE OF SOFTER ASPHALTS." Proceedings, Montana National Bituminous Conference. 1939.

10. Petersen, J.C. "CHEMICAL COMPOSITION OF ASPHALT AS RELATED TO ASPHALT DURABILITY : STATE OF THE ART." Transportation Research Record 999. TRB. Washington, D.C. pp. 13-30. 1984.

11. Welborn, J.Y. "RELATIONSHIP OF ASPHALT CEMENT PROPERTIES TO PAVEMENT DURABILITY." NCHRP Synthesis 59. TRB. National Research Council. Washington, D.C. 1979.

12. Buchanan, J.E. "OBTAINING CRACK FREE PERFORMANCE IN ASPHALT PAVEMENTS." Asphalt Forum. Vol. 11, No. 5. 1938.

13. Traxler, R.W. "DURABILITY OF ASPHALT CEMENTS." Proceedings, AAPT. Vol. 32. pp. 44-58. 1963.

14. Abson, G. "APPARATUS FOR THE RECOVERY OF ASPHALTS." Proceedings, ASTM. Vol. 33, Part. II. 1933.

15. Kumar, A., and W.H. Goetz. "ASPHALT HARDENING AS AFFECTED BY FILM THICKNESS, VOIDS, AND PERMEABILITY IN ASPHALTIC MIXTURES". Proceedings, AAPT. Vol. 46. pp. 571-605. 1977.

16. Kim, O., C.A. Bell, J.E. Wilson, and G. Boyle. "DEVELOPMENT OF LABORATORY OXIDATIVE AGING PROCEDURE FOR ASPHALT CEMENT AND ASPHALT MIXTURES." Transportation Research Record 1115. TRB. Washington, D.C. 1987.

17. American Society for Testing and Materials. "ANNUAL BOOK OF ASTM STANDARDS" Volume 04.03. Philadelphia, PA. 1987.

18. Sisko, A.W. "DETERMINATION AND TREATMENT OF ASPHALT VISCOSITY DATA." Highway Research Record 67. HRB. Washington, D.C. pp. 27-37. 1964.

19. Puzinauskas, V.P. "PROPERTIES OF ASPHALT CEMENTS." Research Report No. 80-2. Asphalt Institute. College Park, M.D. 1980.

20. SAS Institute, Inc. "SAS USER'S GUIDE : STATISTICS." Version 5 Edition. Cary, N.C. 1985.

21. Hicks, C.R. "FUNDAMENTAL CONCEPTS IN THE DESIGN OF EXPERIMENTS." Third Edition. Holt, Rineart, and Winston, Inc. 1982.

22. Button, J.W., D.N. Little, and B.M. Gallaway. "INFLUENCE OF ASPHALT TEMPERATURE SUSCEPTIBILITY ON PAVEMENT CONSTRUCTION AND PERFORMANCE." NCHRP Report No. 268. TRB. National Research Council. Washington, D.C. 1983.