Effects of Hot Storage on the Properties of Asphalt Concrete Mixtures

Final Report

November 24, 1992

Norman W. Garrick, Assistant Professor
Ramnarayan Nunna, Graduate Assistant

JHR 92-213 Project 89-5

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.

Technical Report Documentation Page

1. Report No. JHR 92-212	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Effects of Hot Storage on the Properties of Asphalt Concrete Mixtures

5. Report Date
November 24, 1992

6. Performing Organization Code

7. Author(s)
Norman W. Garrick
Ramnarayan Nunna

8. Performing Orgainization Report No.
JHR 92-212

9. Performing Organization Name and Address

The University of Connecticut
Department of Civil Engineering
191 Auditorium Road, U-37TI
Storrs, CT 02629

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
None

16. Abstract

The main objectives of this project were: 1) to construct pavement sections for evaluating the long-term effects of storage on pavement performance, and 2) to evaluate the magnitude of the changes in asphalt and asphalt mix properties which occur due to storage at elevated temperatures.

Stored and unstored asphalt concrete mixes were sampled from three different jobs for this study. The mixes were sampled at the plant and also while at the job site. Cores from pavement sections constructed with stored and with unstored mixes were also obtained after the pavements had been down for one year.

Analysis of the results showed an increase in the consistency of the asphalts due to storage. The increase is large for jobs 1 and 3 and is likely to have an effect on the pavement life. Analysis of the indirect tensile strength results also showed an increase in strength due to storage.

Even though there was an increase in consistency with storage, this increase did not appear to affect the amount of effort required to compact the mix. Therefore, this increase in consistency is unlikely to have any significance on the ability to obtain a mat of uniform density during construction.

The consistency and mix-property results for the stored mixes showed that the effect of storage was different for the three jobs. These differences between the jobs are due to the different aggregates used and the differences in the storage conditions.

17. Key Words Asphalt, Asphalt Concrete, Asphalt Pavement, Asphalt Aging, Asphalt Chemical Composition, High Pressure Gel Permeation Chromatography, Storage Silo, Test Road	18. Distribution Statement **No Restrictions**

19. Security Classif. (of this report) **Unclassified**	20. Security Classif. (of this page) **Unclassified**	21. No. of Pages 70	22. Price

Form DOT F 1700.7 (8-72)

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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	mililitres	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

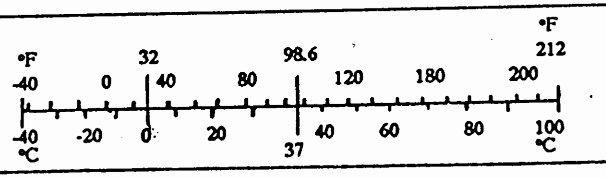
NOTE: Volumes greator than 1000 L shall be shown in m^3.

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



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CHAPTER 1
INTRODUCTION

1.1 Problem Statement

The economic benefits and flexibility of operation of storage silos have led to a marked increase in their use. In 1986, a special report published by the National Asphalt Pavement Association (NAPA) showed that over 83% of asphalt producers nationwide have storage facilities (1).

Storage silos are divided into two categories: 1) surge silos and 2) long-term storage silos. Surge silos are not insulated and the mixes are stored in them for up to six hours. Long-term storage silos are insulated and the mixes are stored at high temperatures for periods of six hours or more.

The changes in mix properties due to storage have created a concern over the increased use of storage silos. If storage significantly affects the mix properties, there could be variabilities in the properties of the mix which is transported to the job site. These variabilities may complicate the construction process and may also reduce pavement durability.

This project was initiated to investigate the effects of prolonged storage at high temperatures on the properties of asphalt and asphalt concrete mixes. The results of the study will help to provide guidelines for regulating the use of hot storage silos. Guidelines so developed may help to optimize pavement durability and may also lead to more efficient use of hot mix silos in pavement construction.

1.2 Research Objectives

The main objectives of this investigation are: 1) to construct pavement sections for evaluating the long term effects of storage on the pavement performance, and 2) to determine the changes in asphalt and asphalt concrete mix properties, which may occur due to storage at elevated temperatures, and to determine how these changes are affected by factors such as mix properties and asphalt composition.

The asphalt properties determined included, viscosity at 275°F, 225°F, 175°F, 140°F and penetration at 77°F. Asphalt composition was characterized by high pressure-gel permeation chromatography (HP-GPC). The mix properties that were determined included the indirect tensile strength and the effort required in compacting the mixes.

1.3 Organization of Report

This report consists of seven chapters. Chapter one contains a description of the purpose and research method of the study. Chapter two is a review of literature on hot storage, high pressure gel permeation chromatography and indirect tension. In Chapter three, the sampling procedure used to collect the test material and the conditions of the silo are discussed. In Chapter four, a detailed description of the test procedure and the equipment used are discussed. The results of the study are presented in Chapter five. An analysis of the results is presented in Chapter six followed by summary and conclusions in Chapter seven.

CHAPTER 2
LITERATURE REVIEW

An overview of research on storage of asphalt concrete mixes is presented in the first section of this chapter. In the second section, the literature on high pressure-gel permeation chromatography is examined in detail. The remainder of the chapter is devoted to a discussion of the laboratory tests on the asphalt concrete mixes.

2.1 Storage of Asphalt Concrete

The installation of storage silos can improve the overall efficiency of a plant by assuring a continuous operation, which results in a higher rate of production and a lower cost of plant operation. Because of the continuous operation, the variabilities in mix composition and temperature associated with starting and with stopping the facility are reduced. Reports show that the use of a surge bin reduces the number of trucks needed, thereby reducing the cost of trucking (2,3).

The first commercial use of silos for long-term storage of asphalt concrete was reported in 1958 (3). Initially, many problems were encountered with the storage, including mix segregation, asphalt migration and heat loss. Most of the problems were reduced during the early 1970's due to improvements in the technology of silo construction (4). In Connecticut, mix segregation is still reported to be a problem in some situations.

Many researchers have tried to estimate the degree of change in asphalt consistency with storage and the factors affecting this change (3,5,6). These studies showed that some increase in consistency does occur in storage. The amount of increase varied depending on the following: 1) the type of atmosphere in the silo (normal or inert), 2) the chemical composition of the asphalt cement, 3) the gradation of the mix, 4) the temperature and duration of storage, and, 5) the use of antioxidants such as silicon. In practice, the use of silicon and inert gas is considered to be unnecessary and is generally not done.

In 1966, Tuttle (2) concluded that asphalt cement hardens significantly if the asphalt concrete mix is stored for prolonged periods at temperatures ranging from 250 to 350°F. The hardening process is continuous and primarily a function of temperature and time. But Middleton, Goodknight, and Eaton (3) reported that there was a marked change in the asphalt cement consistency during mixing in the pugmill, but a negligible change due to storage.

Tunnicliff et al. (4) showed that purging a silo with an inert gas can reduce the amount of change in asphalt consistency associated with asphalt storage. In 1967, Vallerga and White (7) also reported that the rate of hardening can be decreased significantly by adding silicone. Studies conducted by Foster (8,9) in 1967 and 1968 also showed that silicone and inert gas can reduce the rate of hardening significantly and increase the storage time. Brock and Cox (10), in 1968, concluded that storage of mixes is possible without any harmful effects for ten days in a heated silo purged with inert gas, and for more than fourteen days if silicone is added to the mix and the silo is purged with an inert gas.

Studies conducted by Parr and Brock (5) in 1972, Kandhal and Wenger (6) in 1973, Wright and Paquette (11), Hearld, Lay and Shah (12) in 1973, and Zdeb and Brown (13) in 1974, all showed a significant hardening of the asphalt while in storage.

In 1971, the New York State Department of Transportation initiated a long-term research study to determine the effects of storage for prolonged periods (over 12 hours) at temperatures ranging from 250°F to 350°F on the pavement material properties. The mixes for this study were stored in both inert gas and normal atmosphere (14). The initial findings of the study indicated no apparent harmful effects on the properties of asphalt mixes due to the storage (during the first year of the study). But, asphalt hardening was later observed in the stored asphalts recovered from cores sampled over a period of seven years (11,15,16). However, no causative factors for asphalt hardening have been conclusively identified.

As discussed before, the storage of asphalt concrete is influenced by many factors such as, storage conditions, the gradation and asphalt content of the mix, the composition of the asphalt, and the temperature of the mix. Many researchers have attempted to determine the significance of various combinations of these factors, but no single study has provided definitive answers to all questions because of the large number of possible combinations of the different factors.

2.2 Gel Permeation Chromatography

Gel permeation chromatography is one type of high pressure liquid chromatography in which the constituents of a compound are separated based upon molecular size. This technique has been used to characterize and investigate the relationships between the chemical properties and physical properties of the asphalts (18, 19, 24, 26, 27).

As an analytical technique, chromatography has been in use for over 80 years. The term chromatography applies to several related separation techniques, which are all based on the same principle. The substance to be separated is dissolved in a mobile phase and passed through an hetroporous stationary phase. The various dissolved molecules permeate through the stationary phase at different rates and are separated by size as they elute. This technique is used widely and is called liquid or column chromatography. A variant of the simple column technique is High Pressure Liquid Chromatography (HPLC). One of the types of HPLC is termed High Pressure-Gel Permeation Chromatography (HP-GPC).

The first use of the Gel Permeation Chromatography technique on asphalt was published in 1965 by Altgelt (17). Richman (18) in 1967 and Breen and Stephens (19) in 1969, also used this technique to characterize asphalt. Dougan (20) in 1970 found that artificial age hardening of asphalt caused a systematic change in GPC profiles. In same year (1970), Bynum and Traxler (21) related HP-GPC to pavement durability. They analyzed virgin asphalts and core samples from nine sections in Texas. They reported that there were changes in chromatograms for asphalts from a given source over time and also considerable differences among asphalts from different sources.

During the 1970's, several papers were published on various refinements of the HP-GPC technique. The effects of different solvents on molecular weights were reported by Bergmann, Duffy and Stevenson in 1971 (22). In 1978, Dark and McGough (23) used HP-GPC to differentiate between asphalts with different chemical composition. In 1982 Jennings (24) studied the use of solvents other than tetrahydrofuran (THF) as the mobile phase.

Glover, et al. (25), in 1987, conducted a study using Toluene as a mobile phase rather than THF. In this study, the authors listed various factors which could affect the shape of the chromatograms. These factors were:

1) detector sensitivity to different compounds in the sample;
2) type of solvents;
3) sample size and concentration;
4) ultra-violet detector wavelength;
5) column pore size;
6) mobile phase flow rate; and,
7) solution age effects.

Jennings and co-workers at the University of Montana have conducted the most extensive studies on the use of the GPC in predicting asphalt pavement performance (24,26,27,28,29).

Jennings concluded that cracking was related to the relative amount of molecules in the large-molecular-size region of the GPC chromatograms (27,30). Asphalts that performed well in pavements had similar GPC profiles. He also reported that asphalt stiffness increases with an increase in the large-molecular-size (LMS) percentage. In a 1985 study (27), Jennings attempted to correlate climate and road conditions with HP-GPC profiles. He stated that the level of large molecular size (LMS) content above which cracking predominates is a function of climate.

Plummer and Zimmerman's (31) analysis of pavement samples from Michigan and Indiana with HP-GPC supports Jennings' conclusion that large-molecular-size (LMS) percentage is related to pavement cracking. Hattingh (32) also reported that too high an LMS percentage causes cracking and, conversely, too low a percentage causes setting problems.

In 1988 and 1989, Garrick (33,34) presented a method for analyzing HP-GPC profiles by partitioning the area under the profiles into eight equal parts. He developed regression functions by relating the eight HP-GPC parameters to various properties of asphalt cements and asphalt concrete mixes. He also derived a scheme for classifying asphalts on the basis of their GPC profiles, using the relationships developed between GPC parameters and physical properties.

Price (35,36) in 1988 also presented a quantitative method for analyzing HP-GPC profiles by partitioning the area under the profiles into tenths (named as GPC parameters) and relating these parameters to the physical properties of the asphalts and the modified asphalts. The profile was divided into tenths in order to get a better correlation between the GPC parameters and the physical properties of the asphalts and the modified asphalts.

2.3 Indirect Tensile Strength

Indirect tensile strength test is a measure of the tensile strength of an asphalt concrete mix and is frequently used to evaluate pavement performance.

In the indirect tensile strength test, a static load is applied until the specimen fails. Under certain test conditions, the following properties can be determined: Poisson's ratio, modulus of elasticity (E), tensile strain, and compressive strain. Many of these properties are important input parameters for pavement-design procedures that are based on elastic and visco-elastic theory.

The indirect tensile test involves loading a cylindrical specimen with a static compressive load that acts in the vertical diametrical plane, as shown in Figure 1. Specimens four inches in diameter and approximately two-and-one-half inches in height are used. The specimen is loaded in a frame which has a half-inch wide strip on both top and bottom of the specimen to distribute the load and maintain a constant loading area. In this loading configuration, a relatively uniform tensile stress is developed perpendicular to the direction of the applied load and along the vertical diametrical plane. This stress ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter (Figure 1). The stiffness modulus, Poisson's ratio and tensile strength can be estimated by measuring the applied load at failure and by continuously monitoring the load and horizontal and vertical deformations of the specimen.

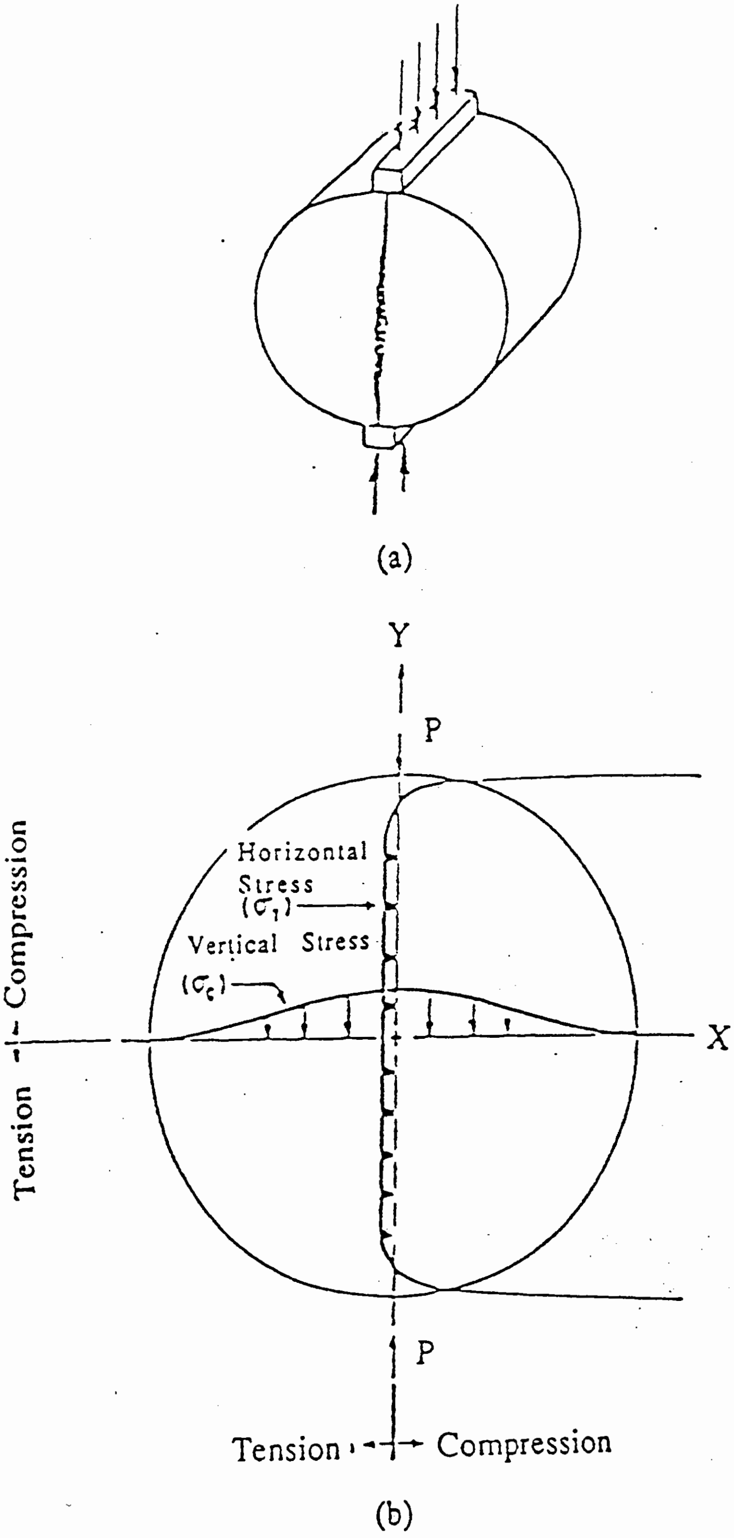


Figure 1. Schematic diagram of (a) Loading and (b) Stress distribution for indirect tensile strength (37)

CHAPTER 3
TEST MATERIALS

The characteristics of the materials used in this research are discussed in this chapter. The first section of this chapter contains a discussion of how the samples were collected. A brief description of the storage conditions in the silo is given in the second section. The final section contains a description of the aggregates used in the study.

3.1 Sampling Process

Connecticut Class I mixes were sampled for this project from three different jobs. Mixes were sampled at the plant and the site from each job. The original asphalts were also sampled from all three jobs.

Information regarding the location of the plants and the sites for the three jobs is given in Table 1. The source and the grades of the asphalts used in the mixes collected from each job are also given in Table. 1.

The mixes from all three jobs were sampled from batch plants. Stored mixes from the silos and unstored mixes coming out directly from the pugmill of the batch plant were sampled at the plant from each job. These mixes were sampled from the truck after it was loaded at the plant. At the site, the mixes were sampled while the truck unloaded the mix into the paver. The mixes sampled at the site were from the same truck sampled at the plant. The mixes sampled at the plants and at the sites from each Job were labeled, plant-stored, plant-unstored, site-stored, and site-unstored, respectively.

The cores from the pavement sections were also obtained after the pavements had been down for one year. The cores were labeled, core-stored, core-unstored.

3.2 Storage Conditions

Stored mixes were sampled from three different jobs. The storage

	PLANT	SITE	SOURCE AND GRADE OF ASPHALT USED
JOB I	TILCON EAST WAUREGAN	ROUTE 101 EAST KILLINGLY	HUDSON AC-20
JOBII	RONCARI EAST GRANBY	ROUTE 159 WINDSOR	HUDSON AC-20
JOBIII	BALF NEWINGTON	ROUTE 85 HEBRON	CHEVRON AC-20

TABLE 1. INFORMATION REGARDING THE JOBS

periods for job 1, job 2, and job 3 were 16, 15 and 15 hours, respectively. The storage conditions were similar for all the jobs and are summarized in Table 2. One important difference between the three jobs is the type of conveyor system used for transporting the mix from the batch plant to the storage silo.

A slat conveyor was used for job 1, a drag conveyor for job 2 and a bucket conveyor for job 3. The main difference between these three systems was the amount of exposure of the material to the atmosphere during its conveyance to the silo. The material in slat and drag conveyor is more exposed to the atmosphere than the material in the bucket conveyor.

3.3 Aggregate, Gradation, and Asphalt Contents of the Mixes

The mixes sampled from all three jobs were Connecticut Class-1 mixes. Granite gneiss and natural sand were used as the aggregate in the mixes sampled from job 1. For jobs 2 and 3, traprock and screened traprock fines were used as the aggregate. Table 3 gives

	JOB I	**JOB II**	**JOB III**
Date	06/15/90	06/27/90	09/26/90
Storage Period	16 Hours	15 Hours	15 Hours
Shape of the bin	Cylindrical	Cylindrical	Cylindrical
Dimensions of the bin	Not Available	14 feet in diameter and 70 feet in height	11 feet in diameter and 80 feet in height
Capacity of the bin	200 tons	300 tons	300 tons
Temperature inside the bin	275°F-320°F	275°F to 320°F	275°F to 320°F
Type of heating system	Electric	Hot oil heating	Hot oil heating
Type of atmosphere (inert or normal)	Normal	Normal	Normal
Type of conveyor used for transporting the mix to the silo	Slat conveyor	Drag conveyor	Bucket Conveyor

TABLE 2. STORAGE CONDITIONS

SIEVE #	PERCENTAGE PASSING						JOB MIX FORMULA
	PLANT 1ST	PLANT 1US	PLANT 2ST	PLANT 2US	PLANT 3ST	PLANT 3US	SPECIFICATION
1	100	100	100	100	100	100	100
3/4	100	99.2	98.3	98.6	100	100	90-100
1/2	97	96.5	86.7	85.7	95.1	95.1	70-100
3/8	70.3	72.0	68.4	68.1	77.1	72.2	60-82
4	45.4	47.2	52.9	51.6	57.2	54.3	40-65
8	36.5	37.1	38.1	40.4	45.4	40.8	28-50
30	23.8	25.1	25.0	25.8	22.6	21	10-32
50	16.2	17.6	16.3	16.8	12.1	13.1	6-26
200	4	4.8	4.6	5.3	4.4	5.6	3-8

TABLE 3. GRADATION OF THE MIXES

the gradations of the stored and the unstored mixes sampled from the three jobs. Table 4 gives the asphalt contents of the stored and the unstored mixes (at the plants) for all jobs.

PLANT1-ST	PLANT1-US	PLANT2-ST	PLANT2-US	PLANT3-ST	PLANT3-US
5.04	5.09	5.26	5.15	5.56	5.59

TABLE 4. ASPHALT CONTENTS OF THE MIXES AT THE PLANTS

CHAPTER 4
EQUIPMENT AND TEST PROCEDURE

This chapter gives a brief description of the equipment and the test procedures used in this research. The procedures discussed are: extraction and recovery procedure of asphalts, tests on asphalt cements, HP-GPC tests and tests on asphalt concrete mixes.

4.1 Extraction and Recovery of Asphalt

Asphalts were extracted from the loose mix and core samples collected from the three jobs. A total of 156 extractions were conducted: 120 extractions from the loose mixes and 36 extractions from the core samples. The asphalt was extracted from the loose mixes and the core samples in accordance with the procedure in ASTM D2172-88. The extracted asphalt was recovered in accordance with the Abson method, ASTM D1856-79 (1984).

4.2 Tests on Asphalt Cements
4.2.1 Physical Properties

Tests to determine the physical properties of the asphalts were conducted on the three original asphalts and on the eighteen recovered asphalt specimens. The recovered asphalts and the original asphalts were tested for the following properties:

1) Penetration at 77°F;
2) Kinematic Viscosity at 275°F;
3) Absolute Viscosity at 140°F;
4) Viscosity at 225°F; and,
5) Viscosity at 175°F.

The penetration test (at 77°F) and the viscosity test (at 275°F and at 140°F) were also conducted on the residue of thin film oven test (TFOT) for the three original asphalts.

All the tests were conducted in accordance with the ASTM procedures. The ASTM test designations for the various tests are given in Table 5. The results of two replications and the average of the replications were reported for each asphalt sample.

TEST	ASTM NUMBER
VISCOSITY(275°F)	D2170
VISCOSITY(225°F)	D2171
VISCOSITY(175°F)	D2171
VISCOSITY(140°F)	D2171
PENETRATION(77°F)	D5
THIN FILM OVEN TEST (T.F.O.T)	D1754

TABLE 5. ASTM DESIGNATIONS FOR TESTS ON ASPHALT CEMENTS

4.2.2 Gel Permeation Chromatography

Gel Permeation Chromatography is a technique in which the constituents of a compound are separated based upon molecular size.

The high pressure-gel permeation chromatography system consists of five components. Figure 2 shows the block diagram of the HP-GPC system. The HP-GPC system includes

1) Milton Roy Constametric 3000, high-pressure pump system;
2) Reodyne model 7125, an injection system;
3) Milton Roy constametric 3100, a multiple wavelength detector;
4) Three Millipore ultrastyragel columns connected in series; and,
5) Shimadzu integrator, chromatopac CR601, data-recording device.

Samples were prepared immediately prior to each injection to avoid the changes which occur in the chemical characteristics of the asphalt with time when it is dissolved in Tetrahydrofuran (THF).

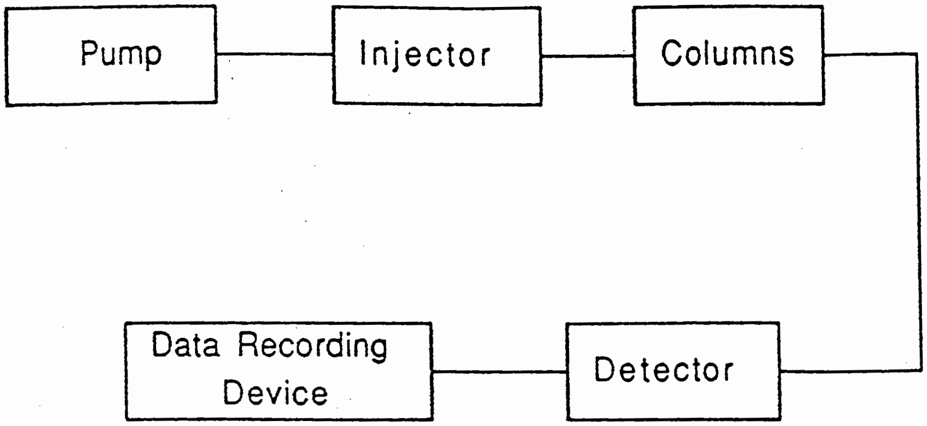


Figure 2. Block diagram of HP-GPC components

The procedure for preparing the samples is as follows:

1) Weigh 20-50 mg of asphalt and transfer it to a small vial;
2) Dilute the asphalt with the volume of THF required to obtain a 0.5 percent solution; and,
3) Filter the solution with 0.45 micron filter remove the fine particles, which could clog the pores of the columns.

The GPC system was equilibrated by pumping THF through the system at a constant flow rate of 1 ml/min for one-and-one-half hours to allow the baseline to stabilize prior to injection.

After the system was equilibrated, 100 microliters of the filtered solution were injected. The injected sample flows through the columns where the separation occurs and the large-size particles elute first followed by medium and small particles. The eluted particles pass through a detector, which measures the amount of particles coming out of the columns at a given time and generates electrical signals which are fed to a integrator. The integrator receives the signals and produces a plot of detector response versus time.

After the analysis is over and before the next sample is injected, the system is purged by injecting 100 microliters of pyridine and pumping tetrahydrofuran (THF) into it at a constant rate of 1 ml/min for sixty minutes. Pyridine effectively cleans out all the adsorbed particles, and prevents any changes in the properties of the column materials.

For this research, the three original asphalts and the eighteen recovered asphalts were analyzed.

4.3 Tests on Asphalt Concrete Mixes

4.3.1 Indirect Tensile Strength Test

The indirect tensile strength tests were conducted on six stored and six unstored mixes. All the tests were conducted at 77°F. Two replications were tested for each sample.

The sample for the indirect tension test were compacted and molded using a gyratory testing machine. The samples were compacted until they had 6 percent air voids. The molded samples were cured at room temperature for twenty four hours prior to the test. The samples were approximately two-and-one-half inches in height and four inches in diameter.

The tests were conducted using a Marshall Testing Machine. The specimens are loaded in a frame which had a half inch strip on both top and bottom of the specimen. A deformation rate of two inches per minute was used.

During loading, the vertical deformation was monitored continuously by graph recorder. The ultimate load or the failure load, which is the load at the point of maximum deformation on the graph, was used to calculate tensile strength using the following equation:

$$S_t = 0.156 \frac{P_f}{H}$$

where,

S_t = Tensile strength, psi;

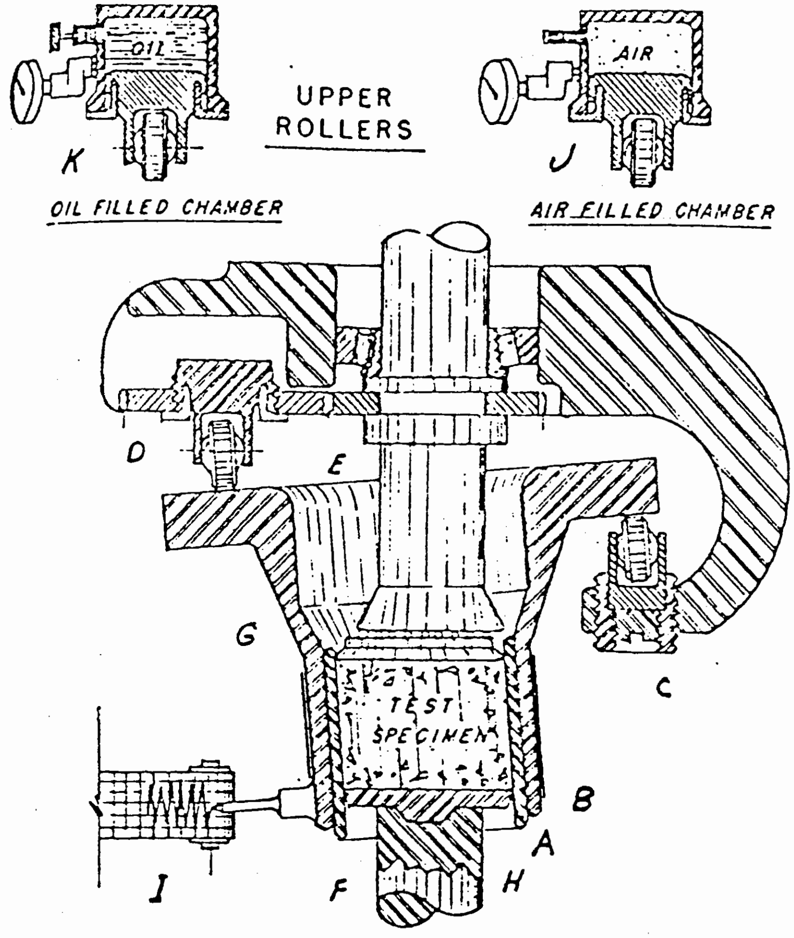
P_f = ultimate load, lbs; and,

H = Height of the specimen.

4.3.2 Ease of Compaction Tests

Ease of compaction tests were conducted to determine the effort required to compact the stored and the unstored mixes sampled from all three jobs. The compaction tests were performed using a gyratory testing machine.

A cross-sectional view of the gyratory mechanism is given in Figure 3. The samples were compacted by a combined kneading and shearing action on the sample while contained in a mold. A vertical pressure is maintained on the samples by hydraulic steel rams, whose faces are parallel to one another.



A. Specimen Mold
B. Mold Chuck
C. Lower Lower
D. Upper Lower
E. Upper Ram Shaft
F. Lower Ram Shaft
G. Upper Head
H. Lower Head
I. Gyrograph

Figure 3. Cross-sectional view of Gyrating Mechanism

The chuck holding the sample mold is mechanized so that it can move with the revolution of the two rollers (lower and upper). In this study the compaction was accomplished using a fixed upper roller with an angle of gyration of one degree.

The samples are placed in the mold and compacted to six percent air voids by controlling the height of the sample using a strip recorder. A vertical pressure of 30 psi was maintained during compaction. The number of revolutions made by the rollers during the compaction is recorded and is reported as the compaction effort.

4.3.3 Density Tests

Density tests were conducted on the stored material and the unstored cores obtained from the pavement sections on all job sites one year after construction. The densities of the cores were measured in accordance with ASTM D2726-89.

CHAPTER 5
TEST RESULTS

This chapter contains the results of tests on asphalts and asphalt concrete mixes.

5.1 Tests on Asphalt Cements
5.1.1 Physical Properties

The results of the viscosity tests (at 275°F, 225°F, 175°F and 140°F) and the results of the penetration tests (at 77°F) are given in Tables 6, 7, 8 and 9, respectively. The results of the Thin Film Oven Test (TFOT) on residues of the original asphalts are also included in these Tables.

Based on the ASTM standard 3515, the maximum allowable viscosity of the asphalt cement recovered from stored mixes at the plant should be equal to or less than 10,000 poises at 140°F. The results in the Table 6 show that the stored asphalts from job 1 do not meet the ASTM standards. The viscosity of the stored asphalt at the plant from job 1 is 12,972 poises (at 140°F). The viscosities of the stored asphalts at the plant from jobs 2 and 3 (shown in the Tables 7 and 8) meet the ASTM standards.

	275°F cst			225°F poises			175°F poises			140°F poises		
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
ORIGINAL	401	406	404	24	23	24	236	245	241	2073	2056	2065
T.F.O.T	673	684	679	-	-	-	-	-	-	5557	5546	5552
PLANT-ST	1022	1008	1015	63	68	66	1237	1190	1214	13023	12920	12972
SITE-ST	828	801	815	48	49	49	842	845	844	8692	7982	8337
CORE-ST	988	997	993	57	60	59	1076	1140	1108	13529	13369	13449
PLANT-US	603	613	608	31	31	31	426	440	433	3678	3689	3684
SITE-US	656	659	658	38	38	38	534	509	522	4446	4232	4339
CORE-US	792	789	791	48	51	50	861	765	813	8874	8897	8886

TABLE 6. VISCOSITY RESULTS FOR JOB 1

		275°F cst			225°F poises			175°F poises			140°F poises	
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
ORIGINAL	410	404	407	21	23	22	241	251	246	2145	2172	2159
T.F.O.T	647	647	647	-	-	-	-	-	-	5617	5613	5615
PLANT-ST	663	667	665	46	46	46	742	629	686	5270	4826	5048
SITE-ST	695	699	697	48	49	49	848	776	812	5728	6258	5993
CORE-ST	850	855	853	53	63	58	1152	1200	1176	11362	10648	11005
PLANT-US	667	629	648	42	39	41	726	653	690	4228	4311	4270
SITE-US	669	694	682	42	44	43	854	768	811	5477	5472	5475
CORE-US	793	785	789	49	49	49	797	748	773	10134	9355	9745

TABLE 7. VISCOSITY RESULTS FOR JOB 2

		275°F cst			225°F poises			175°F poises			140°F poises	
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
ORIGINAL	502	498	500	23	24	24	282	260	271	1977	2054	2016
T.F.O.T	670	680	675	-	-	-	-	-	-	5551	5468	5510
PLANT-ST	1082	1020	1051	73	69	71	1113	1066	1090	8563	8595	8579
SITE-ST	1262	1250	1256	100	103	102	1792	1858	1825	23804	21609	22707
CORE-ST	1443	1457	1450	109	110	110	2116	2627	2372	30513	30237	30375
PLANT-US	830	823	827	53	50	52	897	909	903	8472	8542	8507
SITE-US	832	831	832	51	52	52	907	923	915	8580	8380	8380
CORE-US	1007	1027	1017	56	68	62	1167	1242	1205	13973	13957	13957

TABLE 8. VISCOSITY RESULTS FOR JOB 3

	JOB I			JOB II			JOB III		
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
ORIGINAL	74	74	75	75	76	76	70	70	70
T.F.O.T	43	43	43	41	40	41	44	44	44
PLANT STORED	35	35	35	49	48	49	37	36	37
SITE STORED	44	43	44	45	45	45	30	30	30
CORE STORED	35	35	35	37	39	38	28	27	28
PLANT UNSTORED	57	58	58	51	52	52	39	39	39
SITE UNSTORED	52	51	52	43	43	43	39	39	39
CORE UNSTORED	38	40	39	40	41	41	34	33	34

TABLE 9. PENETRATION RESULTS IN 0.01 MM AT 77°F

5.1.2 Temperature Susceptibility

Temperature susceptibility is a property that measures the rate of change of the asphalt consistency with temperature. This property is used to estimate low-temperature properties, and hence, the cracking potential of the asphalt mixes. For asphalts of a given grade, the one that is more temperature susceptible will be stiffer at lower temperatures and will be more likely to crack.

The temperature-susceptible indices that were calculated included viscosity-temperature susceptibility (VTS), penetration-viscosity number (PVN) and penetration-viscosity number (PVN'). The equations used for calculating VTS, PVN and PVN' are given in Table 10.

VTS is an indicator of the temperature susceptibility in the temperature range from 140°F to 275°F. PVN is based on the measurements of penetration at 77°F and of viscosity at 275°F. High values indicate lower temperature susceptibility, and vice versa. PVN' is an indicator of the temperature susceptibility based on viscosity measured at a lower temperature. PVN' is similar to PVN except that it is based on the measurements of penetration at 77°F and of viscosity at 140°F. Asphalts with more negative PVN or PVN' values are more temperature-susceptible.

The temperature-susceptibility results are given in Table 11. The results in Table 11 show that the original asphalt from job 3 is the most temperature susceptible and the original asphalt from job 2 is the least temperature susceptible at low temperatures. The differences, however, are small. The stored asphalts are less temperature susceptible than the unstored asphalts at lower temperatures.

a) Viscosity-Temperature Susceptibility, VTS(140-275)

$$\mathrm{VTS}(140\text{-}275) = \frac{\mathrm{LogLog}(V275)-\mathrm{LogLog}(V140)}{\mathrm{Log}(333)-\mathrm{Log}(408)}$$

where,

VTS(140-275) = Viscosity Temperature Susceptibility
V275 = Viscosity at 275°F in centi-poises
V140 = Viscosity at 140°F in centi-poises

b) Penetration - Viscosity Number, PVN(77-275)

$$\mathrm{PVN} = \frac{-1.5[A-\mathrm{Log}(V275)]}{A-B}$$

where,

A = 4.258 - 0.79674Log(P77)
B = 3.46289 - 0.61094Log)P77)
V275 = Viscosity at 275°F in centi-stokes
P77 = Penetration in 0.1 mm at 77°F

c) Penetration - Viscosity Number, PVN'(77-140)

$$\mathrm{PVN'} = \frac{-1.5\{[6.489-1.59\mathrm{Log}(P77)]-\mathrm{Log}(V140)}{1.05-0.2234\mathrm{Log}(P77)}$$

where,

V140 = Viscosity at 140°F in poises
P77 = Penetration in 0.1 mm at 77°F

TABLE 10. EQUATIONS FOR CALCULATING TEMPERATURE SUSCEPTIBILITY

SAMPLE	VTS(140-275)	PVN(77-275)	PVN'(77-140)
ORGINAL-1	3.56	-0.51	-0.46
TFOT-ORIGINAL	3.53	-0.38	-0.32
PLANT-STORED	3.54	-0.06	+0.17
SITE-STORED	3.54	-0.12	+0.10
CORE-STORED	3.57	-0.10	+0.20
PLANT-UNSTORED	3.46	-0.22	-0.30
SITE-UNSTORED	3.46	-0.23	-0.28
CORE-UNSTORED	3.59	-0.28	-0.06
ORGINAL-2	3.57	-0.50	-0.39
TFOT-ORIGINAL2	3.57	-0.49	-0.38
PLANT-STORED	3.51	-0.28	-0.22
SITE-STORED	3.53	-0.30	-0.18
CORE-STORED	3.60	-0.20	+0.10
PLANT-UNSTORED	3.46	-0.25	-0.21
SITE-UNSTORED	3.52	-0.38	-0.34
CORE-UNSTORED	3.62	-0.23	+0.10
ORGINAL-3	3.33	-0.30	-0.59
TFOT-ORIGINAL3	3.52	-0.37	-0.30
PLANT-STORED	3.36	+0.04	-0.14
SITE-STORED	3.57	+0.05	+0.45
CORE-STORED	3.57	+0.16	+0.61
PLANT-UNSTORED	3.53	-0.22	-0.06
SITE-UNSTORED	3.54	-0.21	-0.08
CORE-UNSTORED	3.54	-0.09	+0.19

TABLE 11. TEMPERATURE SUSCEPTIBILITY RESULTS

5.2 Tests on Asphalt Concrete Mixes

5.2.1 Indirect Tensile Strength Results

Indirect tensile strength tests were conducted on six stored and six unstored mixes at 77° F. The two replications were reported for each sample and are given in Table 12. From the results in the table, it is seen that the indirect tensile strengths of the mixes from job 1 are higher than those of the mixes from jobs 2 and 3. These differences are most likely caused by the differences in the aggregates used in the mixes. Mixes from job 1 had granite gneiss and natural sand. Mixes from jobs 2 and 3 both had traprock and screened traprock fines.

	JOB I			JOB II			JOB III		
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
PLANT STORED	190	206	198	134	136	135	149	158	154
SITE STORED	186	190	188	151	154	152	161	176	169
PLANT UNSTORED	166	169	168	133	129	131	140	150	145
SITE UNSTORED	188	183	185	139	140	140	148	148	148

TABLE 12. INDIRECT TENSILE STRENGTH IN PSI, AT 77°F

5.2.2 Ease of Compaction Test Results

The compaction tests were conducted on six stored and six unstored mixes. The two replications for each sample were reported and the results are given in Table 13. The effort required to compact the mixes from job 1 is higher than the efforts required to compact the mixes from jobs 2 and 3. As with the indirect tensile strength results, the differences in the compaction efforts are probably also due to the fact that the aggregate used in job 1 was different from that used in jobs 2 and 3.

	JOB I			JOB II			JOB III		
	#1	#2	Avg	#1	#2	Avg	#1	#2	Avg
PLANT STORED	41	41	41	27	27	27	26	27	27
SITE STORED	41	42	42	26	26	26	28	28	29
PLANT UNSTORED	42	45	43	26	25	26	27	27	27
SITE UNSTORED	41	45	43	26	27	27	27	27	27

TABLE 13. COMPACTION EFFORT RESULTS, NUMBER OF REVOLUTIONS

5.2.3 Density Results

The densities were measured of the cores obtained from the stored and the unstored pavement sections after one year. The results are given in Table 14.

	JOB I	JOB II	JOB III
SITE-STORED	151	155	142
SITE-UNSTORED	146	153	144

TABLE 14. DENSITIES OF THE CORES, IN LBS/FT^3

5.3 HP-GPC Results

The HP-GPC technique is used to characterize the chemical composition of the asphalts. Three original asphalts samples, three original thin-film samples and eighteen recovered-asphalt samples were characterized and the results are reported. The results of the HP-GPC runs are given in the Table 15.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14
ORG1	1.554	8.127	11.905	15.553	20.583	20.312	13.124	5.745	1.978	0.533	0.307	0.183	0.083	0.012
TOR1	2.052	9.979	12.619	15.123	19.839	19.492	12.439	5.409	1.833	0.515	0.302	0.205	0.134	0.064
P1ST	0.884	7.484	12.985	16.887	20.446	19.521	12.682	5.689	2.024	0.669	0.401	0.232	0.096	0.010
S1ST	0.748	8.431	13.186	14.151	18.165	19.469	14.599	7.065	2.790	0.691	0.391	0.215	0.102	0.028
C1ST	2.628	10.950	13.199	16.094	20.062	18.459	11.014	4.708	1.525	0.536	0.359	0.265	0.159	0.055
P1US	0.580	7.284	12.063	14.191	19.231	20.769	14.937	6.999	2.686	0.641	0.321	0.190	0.091	0.018
S1US	0.871	8.015	12.323	14.387	19.323	20.393	14.222	6.547	2.521	0.659	0.364	0.231	0.117	0.024
C1US	2.214	10.473	12.874	16.166	20.208	18.584	11.140	4.843	1.696	0.700	0.474	0.334	0.217	0.079
ORG2	1.525	8.346	12.524	16.592	21.440	19.962	12.049	4.936	1.556	0.477	0.301	0.186	0.088	0.018
TOR2	1.876	10.063	13.097	15.574	20.059	19.245	12.085	5.100	1.699	0.492	0.298	0.210	0.144	0.056
P2ST	1.093	8.242	12.990	14.675	19.053	19.814	14.064	6.450	2.458	0.581	0.296	0.179	0.088	0.018
S2ST	1.433	9.347	13.207	15.707	19.917	19.390	12.663	5.411	1.855	0.481	0.289	0.187	0.101	0.017
C2ST	2.797	11.426	13.890	16.790	20.185	17.791	10.213	4.196	1.316	0.513	0.378	0.285	0.169	0.056
P2US	1.159	8.003	12.791	15.802	20.062	19.574	12.929	5.748	2.217	0.744	0.493	0.307	0.149	0.024
S2US	0.719	8.101	13.249	14.692	19.117	19.975	14.068	6.338	2.438	0.624	0.340	0.203	0.108	0.035
C2US	1.621	9.848	13.533	15.837	20.134	19.405	11.900	4.870	1.669	0.497	0.295	0.200	0.137	0.066
ORG3	1.699	9.226	12.948	16.947	21.186	19.323	11.421	4.657	1.509	0.484	0.300	0.190	0.093	0.014
TOR3	2.301	10.344	13.146	15.952	20.421	19.124	11.399	4.640	1.546	0.469	0.283	0.191	0.128	0.062
P3ST	1.720	9.980	13.507	15.154	19.257	19.244	12.560	5.280	1.900	0.585	0.373	0.259	0.140	0.041
S3ST	1.462	10.254	13.754	14.069	17.786	18.869	13.600	6.241	2.485	0.704	0.370	0.238	0.132	0.039
C3ST	2.294	10.943	14.104	15.729	19.351	18.469	11.318	4.690	1.674	0.538	0.349	0.268	0.176	0.077
P3US	1.254	9.100	13.127	14.748	19.456	20.041	13.261	5.650	2.093	0.586	0.323	0.177	0.132	0.049
S3US	1.687	9.789	13.298	14.715	19.284	19.718	12.875	5.430	1.996	0.568	0.261	0.195	0.111	0.030
C3US	2.551	10.895	13.531	16.482	20.092	18.086	10.747	4.480	1.470	0.603	0.446	0.340	0.231	0.054

TABLE 15. HP-GPC RESULTS

CHAPTER 6
ANALYSIS OF RESULTS

This chapter presents the analysis of the results for the tests on the asphalts and on the asphalt concrete mixes.

6.1 Statistical Model

An analysis of variance was performed on test results for both asphalt cements and asphalt concrete mixes. The purpose of the analysis was to determine if there were statistically significant differences between the properties of the stored and the unstored mixes from the three jobs.

The statistical model used to analyze the data is as follows:

$$Y_{ijk} = M + A_i + B_j + C_k + E_{ijkl}$$

where,

Y_{ijk} = Variable to be analyzed

M = Overall mean

A_i = Type of mix
$i=1$, Stored mix
$i=2$, Unstored mix

B_j = Jobs
$j=1$, Job1
$j=2$, Job2
$j=3$, Job3

C_k = Stage of mix
$k=1$, Plant
$k=2$, Site
$k=3$, Core

E_{ijkl} = Error

In the above model, the dependent variable, Yijk, is the test parameter being evaluated. This test parameter can be viscosity and penetration for asphalt cements, or indirect tension and ease of compaction for asphalt concrete mixes.

The null hypothesis tested in the analysis of the results is that there are no differences between the stored and the unstored mixes. The acceptance of the null hypothesis indicates that no significant change occurred due to storage. The null hypothesis is tested using an F-test at the significance level of 0.05.

6.2 Analysis of Consistency Results

6.2.1 Analysis of Viscosity Results

Viscosity ratios were used to study the changes in the asphalts from the stored and the unstored mixes. Viscosity ratio is the ratio of viscosity of the recovered asphalt to the viscosity of the original asphalt. The analysis of variance was performed on the viscosity ratios calculated at 275°F, 225°F, 175°F and 140°F.

Table 16 shows that the null hypothesis is rejected for jobs 1 and 3, and accepted for job 2. This indicates that, for jobs 1 and 3, the stored asphalts have higher mean viscosities than the unstored asphalts. In contrast, the differences between the stored and the unstored asphalts, for job 2, are not significant at the 0.05 significance level. This trend was the same for viscosities at all temperatures.

Figures 4, 5 and 6 show the viscosities at 140°F for the stored and the unstored asphalts at different stages of sampling (at plant, at site, after one year in the road) for jobs 1, 2 and 3 respectively. In most cases, the viscosity of the stored and the unstored asphalts increased from plant to site and from site to core. The increase in viscosity is due to the aging of the asphalt during trucking from plant to site and during one year of service in the field.

There is one exception to the pattern of increase in viscosity that is discussed above. For job 1, the viscosity of the stored asphalt decreased from plant to site (see Figure 4). It is unlikely that the viscosity would decrease in this manner from plant to site since one would expect the viscosity to increase due to aging with time. It is felt, therefore, that this result might be due to a sampling error.

	$275^{O}F$	$225^{O}F$	$175^{O}F$	$140^{O}F$
JOB I	$H_O : M_{st} <= M_{us}$ **p*-value**=0.0008 $\mathbf{H_O}$ is Rejected at 0.05 significance level	H_O : Mst<=Mus **p*-value**=0.0034 $\mathbf{H_O}$ is Rejected at 0.05 significance level	H_O : Mst<=Mus **p*-value**=0.0009 $\mathbf{H_O}$ is Rejected at 0.05 significance level	H_O : Mst<=Mus **p*-value**=0.0023 $\mathbf{H_O}$ is Rejected at 0.05 significance level
JOB II	**p*-value**=0.5017 $\mathbf{H_O}$ is Accepted at 0.05 significance level	**p*-value**=0.0583 $\mathbf{H_O}$ is Accepted at 0.05 significance level	**p*-value**=0.2041 $\mathbf{H_O}$ is Accepted at 0.05 significance level	**p*-value**=0.5656 $\mathbf{H_O}$ is Accepted at 0.05 significance level
JOB III	**p*-value**=0.0015 $\mathbf{H_O}$ is Rejected at 0.05 significance level	**p*-value**=0.0006 $\mathbf{H_O}$ is Rejected at 0.05 significance level	**p*-value**=0.0142 $\mathbf{H_O}$ is Rejected at 0.05 significance level	**p*-value**=0.0360 $\mathbf{H_O}$ is Rejected at 0.05 significance level

*= Probability value. If p is less than 0.05 reject H_O otherwise Accept H_O

TABLE 16. HYPOTHESIS TESTS FOR THE VISCOSITY RATIOS OF THE ASPHALTS FROM THE STORED AND THE UNSTORED MIXES AT $275^{O}F$, $225^{O}F$, $175^{O}F$ AND $140^{O}F$

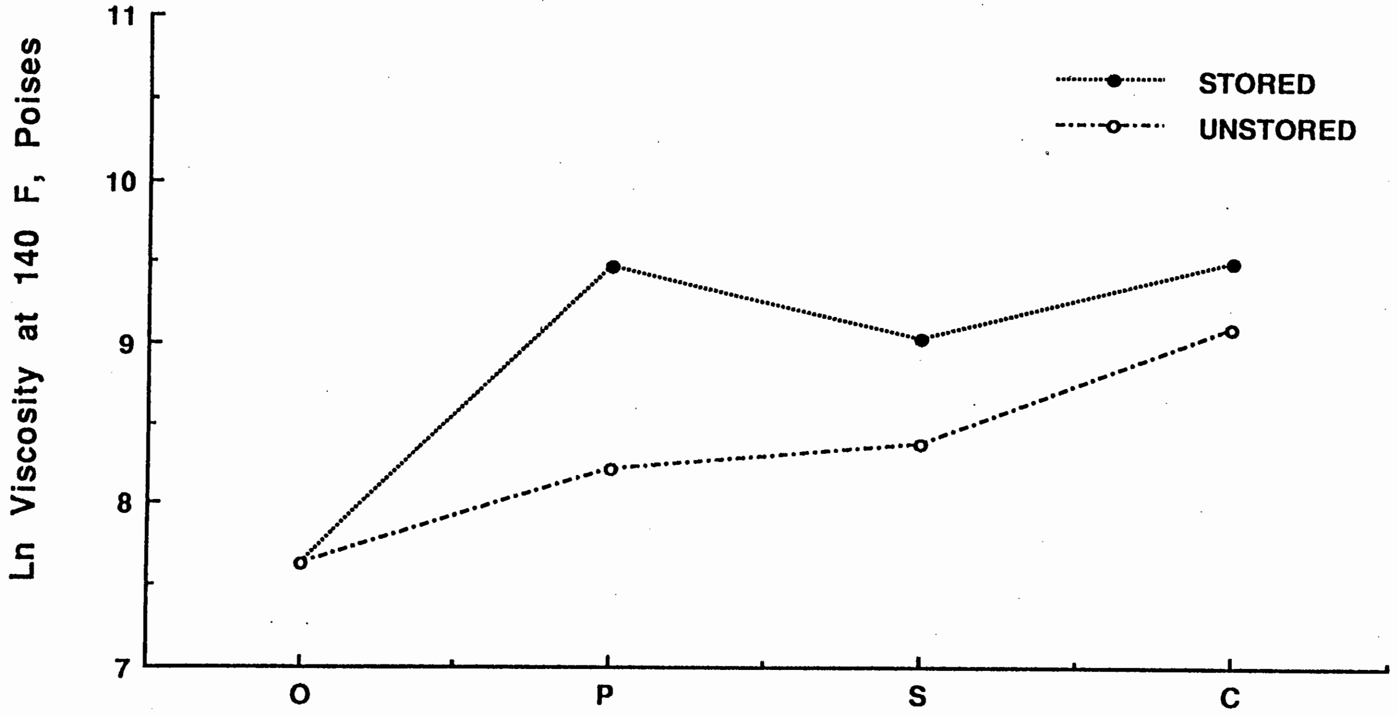


Figure 4. Change in viscosities of the stored and the unstored asphalts from job 1

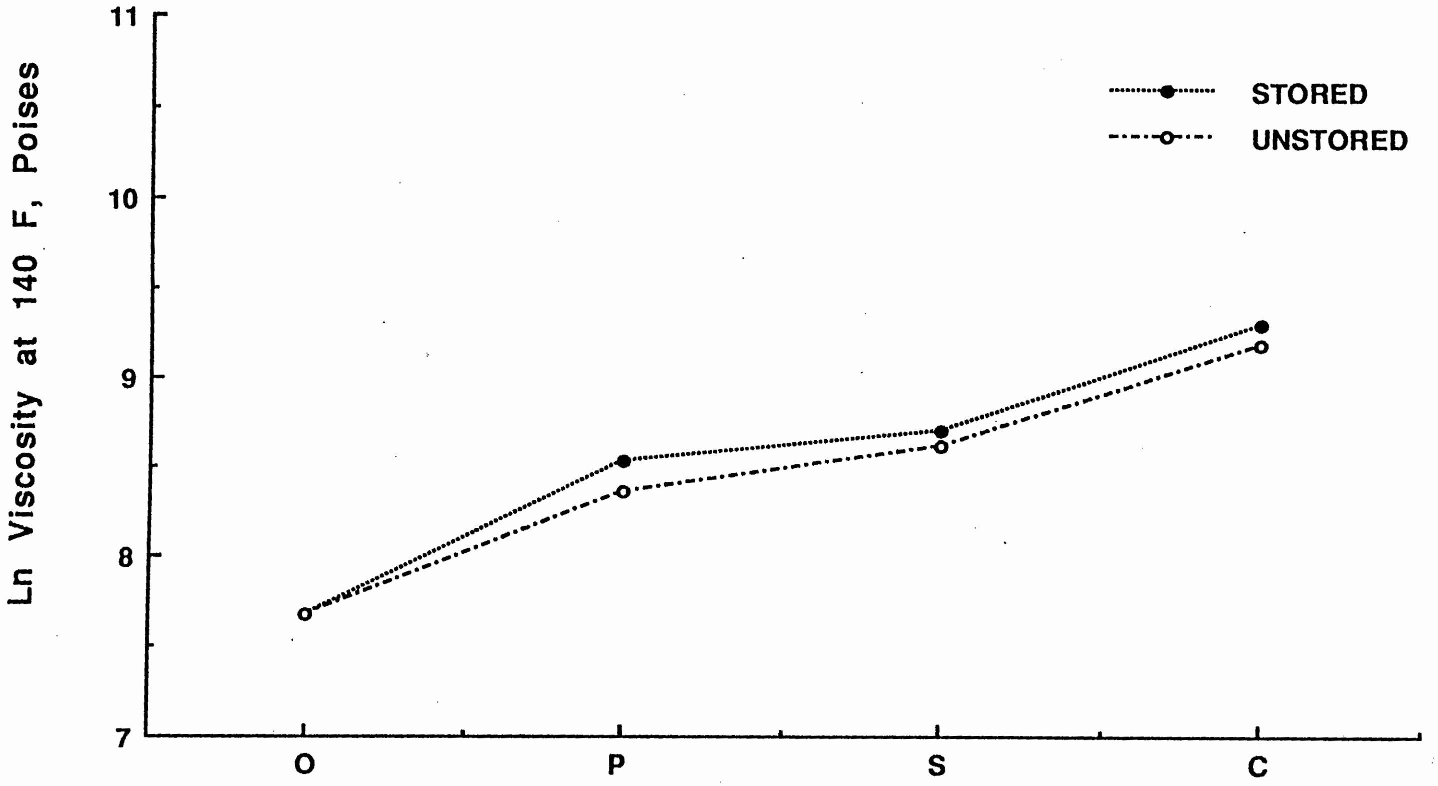


Figure 5. Changes in viscosities of the stored and the unstored asphalts from job 2

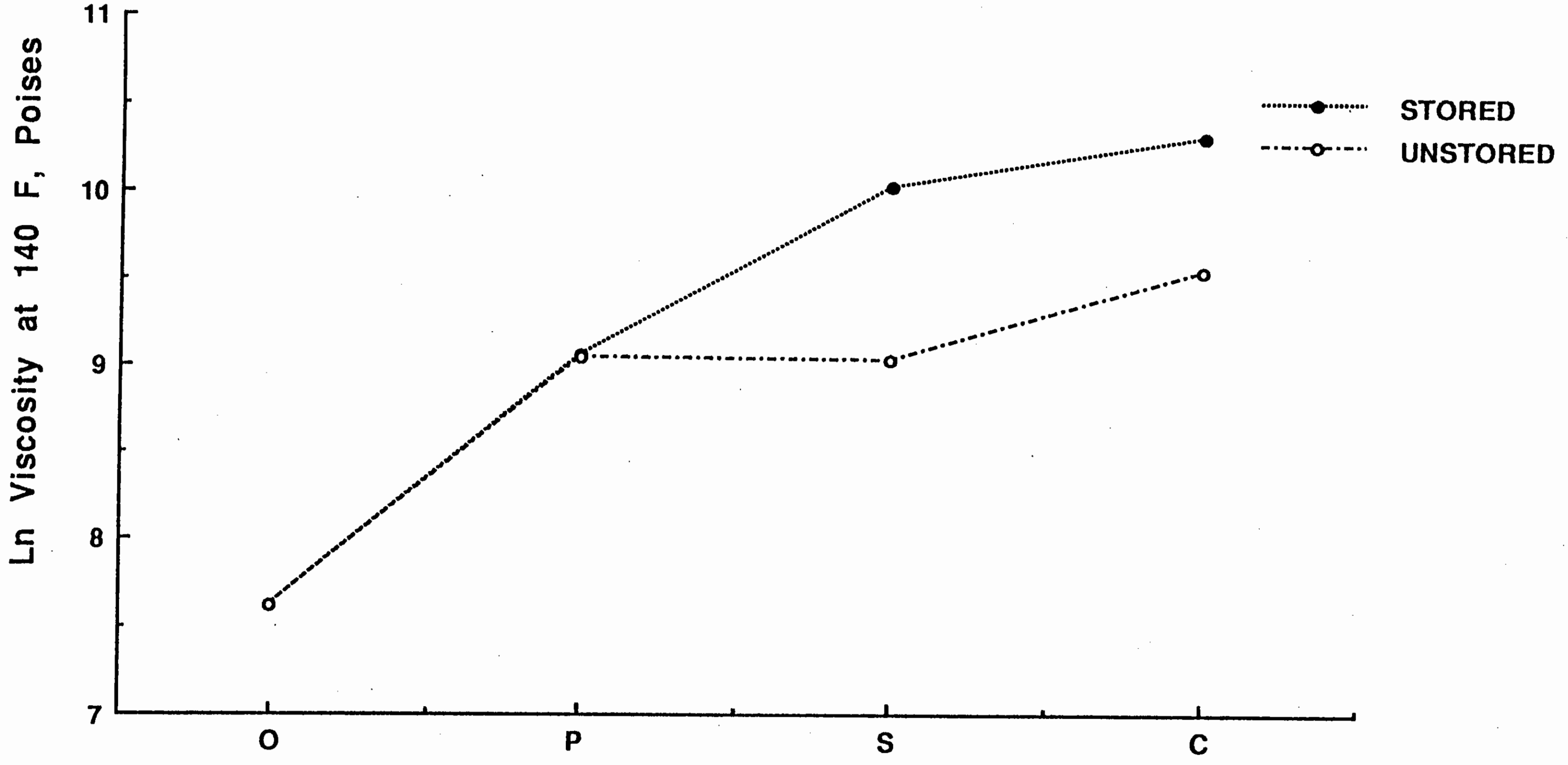


Figure 6. Changes in viscosities of the stored and the unstored asphalts from job 3 .

If the anomaly discussed in the last paragraph is ignored, Figures 4, 5 and 6 show that the curves for the stored and the unstored asphalts for each job are basically parallel. The viscosity of the stored asphalts are generally higher than the unstored asphalts. The curve for the stored asphalts represents the changes in asphalts due to the combined effects of mixing and storage. While the curves for the unstored asphalts represents the effects of mixing only, the changes due to the storage can, therefore, be estimated from the difference or shift between the curves for the stored and the unstored asphalts. Conversely, the changes due to mixing can be estimated from the difference between the viscosity of the unstored asphalt at the plant and the viscosity of the original asphalt.

In other words, the changes due to the storage can be estimated from the average of the ratio of the viscosity of the stored and the unstored asphalts at different stages of sampling (at plant, at site, at core). While the changes due the mixing can be estimated from the ratio of the viscosity of the unstored asphalt at the plant to the viscosity of the original asphalt.

The estimated changes in the viscosities due to mixing, storage and, the combined effects of the mixing and storage are given in Table 17 for the three jobs.

	CHANGE DUE TO MIXING	CHANGE DUE TO STORAGE	TOTAL CHANGE DUE TO MIXING AND STORAGE
JOB 1	1.78	2.32	4.13
JOB 2	1.98	1.13	2.23
JOB 3	4.22	1.96	8.27

TABLE 17. THE EFFECTS OF MIXING AND STORAGE ON VISCOSITY AT 140°F

The results in the table show that the overall change due to mixing and storage is largest for job 3. The increase in viscosity of the asphalts due to mixing and storage is more than eight times that of the original viscosity. Most of the change, however, occurred in mixing (4 times) rather than during storage (2 times).

The viscosity of the asphalts from the job 1 increased by four times due to mixing and storage. Unlike job 3, however, most of the change is due to storage (2.3 times) rather than to the mixing (1.8 times). Job 2 is more like job 3 in that most of the change occurred during mixing (2 times). However, the overall change for job 2 is much smaller than for job 3 since the change due to storage is negligible.

6.2.2 Analysis of Penetration Results

Analysis of variance was performed on the penetration results at 77°F. The analysis shows that the effect of storage is significant for jobs 1 and 3, but not for job 2, at the 0.05 level of significance. These results are similar to the viscosity results.

The penetrations for the stored and the unstored asphalts are shown in the Figures 7, 8 and 9 for the jobs 1, 2 and 3, respectively. Figures 7, 8 and 9, like the Figures 4, 5 and 6, show that the curves for the stored and the unstored asphalts are essentially parallel. In most cases, the penetration of the stored and the unstored asphalts decreased from plant to site and from site to core.

For job 1, the penetration of the stored asphalt increased from plant to site (see Figure 7). It is unlikely that the penetration would increase in this manner from plant to site, since one would expect the penetration to decrease due to aging with time. This anomaly was also manifested in the viscosity results. As discussed before, it is thought that this result might be due to a sampling error.

6.3 HP-GPC Profiles

The HP-GPC system was used in this study to characterize the asphalt composition of the asphalt cements. The HP-GPC system allows the largest molecules to pass most quickly through the columns but successively retards the progress of the small molecules.

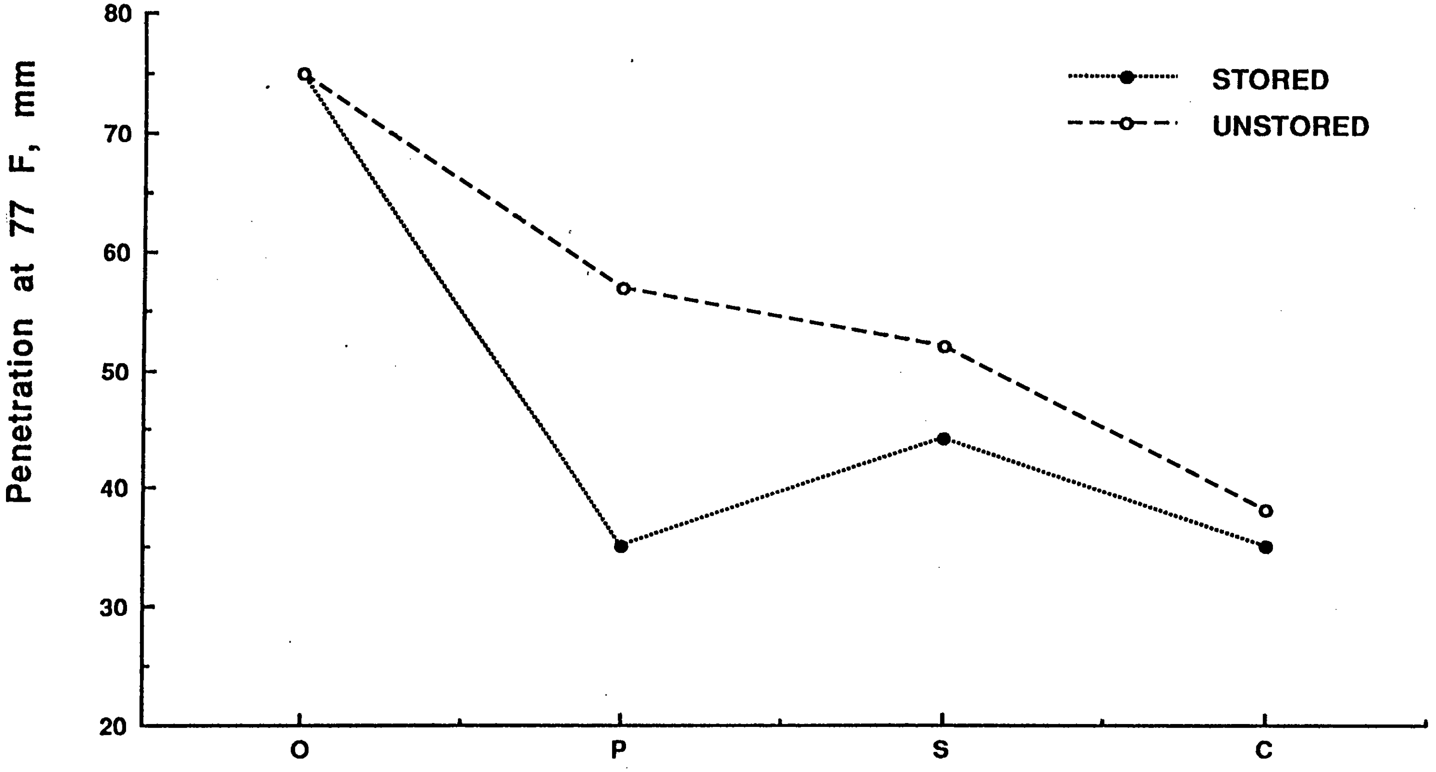


Figure 7. Change in penetration of the stored and the unstored asphalts from job 1

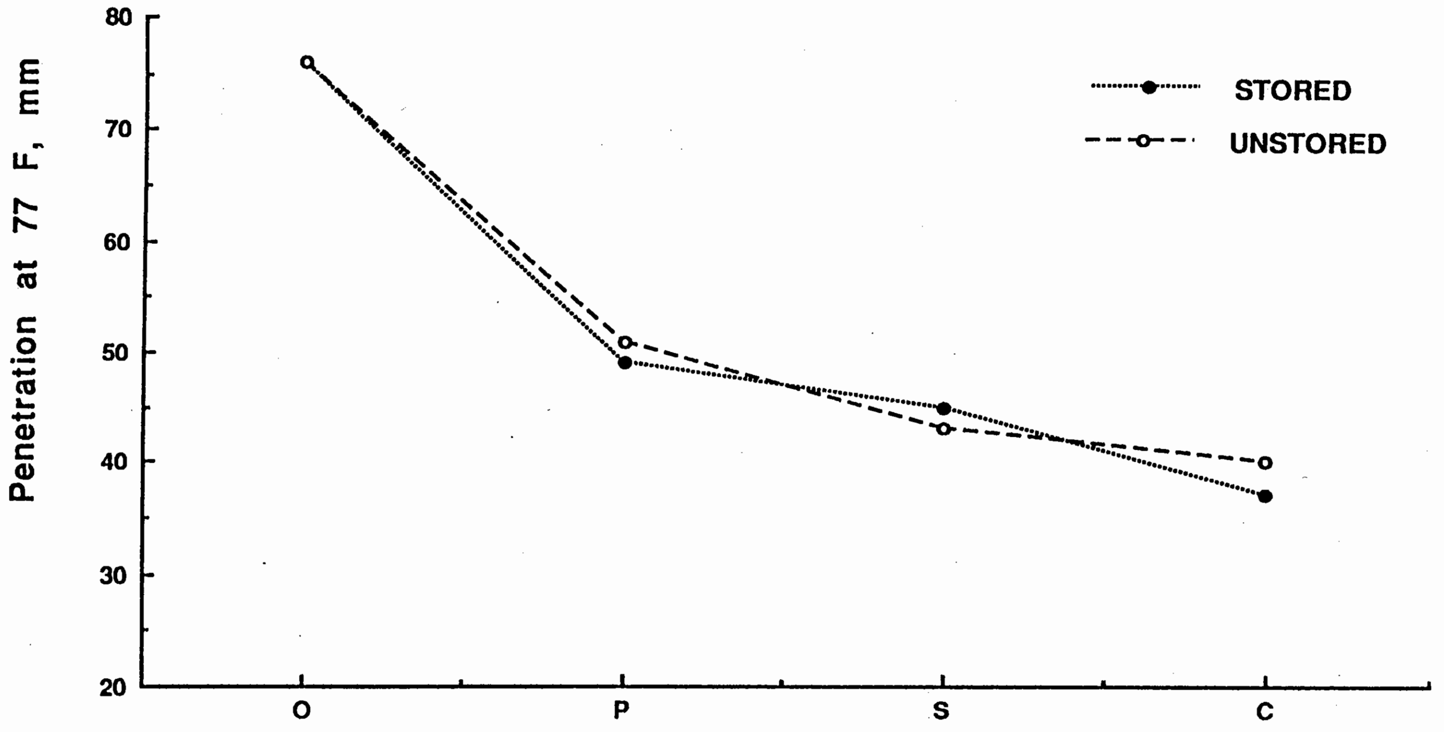


Figure 8. Change in penetration of the stored and the unstored asphalts from job 2

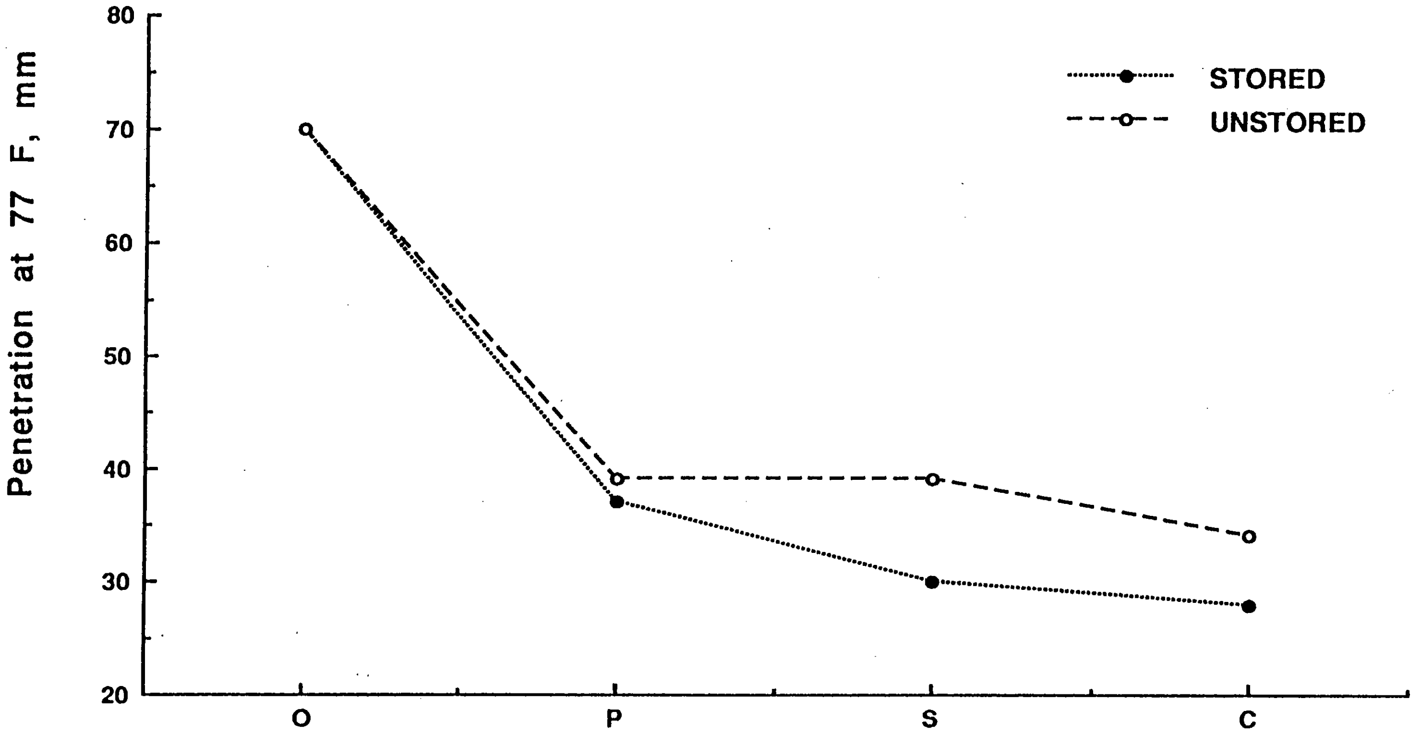


Figure 9. Change in penetration of the stored and the unstored asphalts from job 3

In this study, the HP-GPC parameters were obtained from the HP-GPC profiles using the procedure developed by Garrick and Wood (33,34). The area under the original GPC profile was divided into 14 equal parts (areas) and each part (area) was designated as one parameter. To facilitate comparison, the profiles are redrawn using the 14 HP-GPC parameters on the x-axis and percent of total area on the y-axis so that all the profiles have equal area under the curve.

Profiles of the original asphalts, and the stored asphalts and the unstored asphalts from three jobs were compared visually. The comparison was done to determine the differences in composition between the original asphalts from the three jobs, the changes in composition of the recovered asphalts from the three jobs due to storage and, the effect of aging from plant to site and from site to one year of service.

6.3.1 Comparison of Original Asphalt Profiles

The profiles of the original asphalts from the three jobs are compared in the Figure 10. The Figure shows that the asphalts from the three jobs have similar profiles. The profile from job 3 shows more apparent large molecules than the profiles from jobs 1 and 2. The profile from job 2, in turn, shows more apparent large molecules than the profile from job 1. The differences, however, are very small. Thus, the chemical composition is not very different for the asphalts from the three jobs.

6.3.2 Comparison of Stored and Unstored Profiles

The GPC profiles of the stored and the unstored asphalts sampled at the plant for jobs 1, 2 and 3 were compared in the Figures 11, 12 and 13, respectively. The profiles in the Figures 11 and 13, for the jobs 1 and 3, show that there are small differences between the stored and the unstored asphalt profiles with the stored profile showing more apparent large molecules than the unstored asphalt profiles. In contrast, Figure 12, shows for job 2, that there are essentially no differences between the stored and the unstored asphalt profiles. This is consistent with the fact that the changes due to storage are almost negligible for job 2.

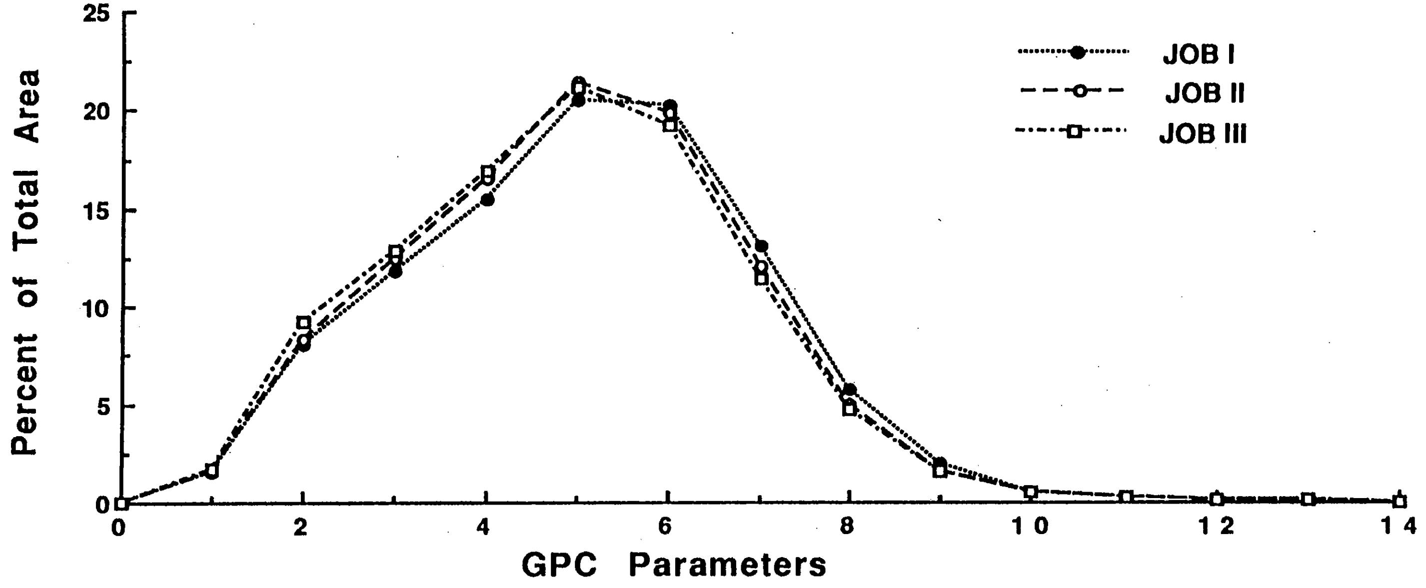


Figure 10. HP-GPC profiles for original asphalts

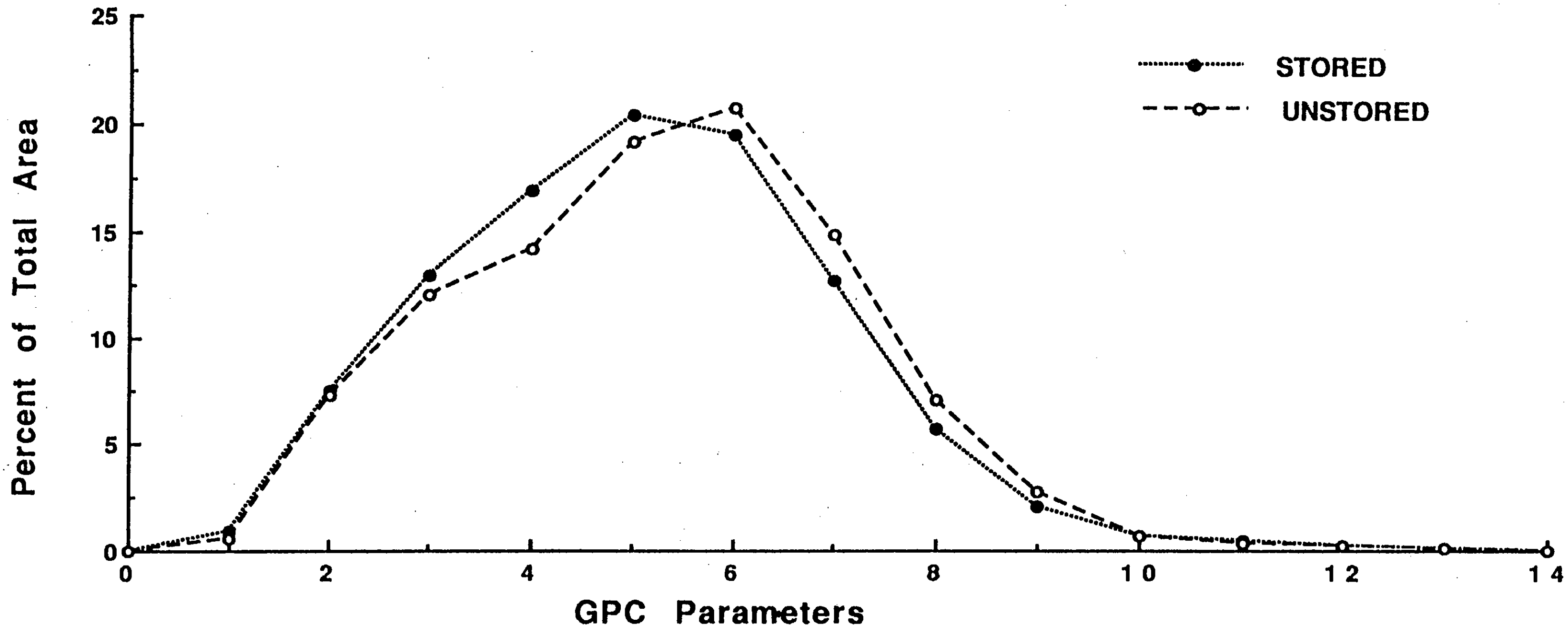


Figure 11. HP-GPC profiles for stored & unstored asphalts at plant from job 1

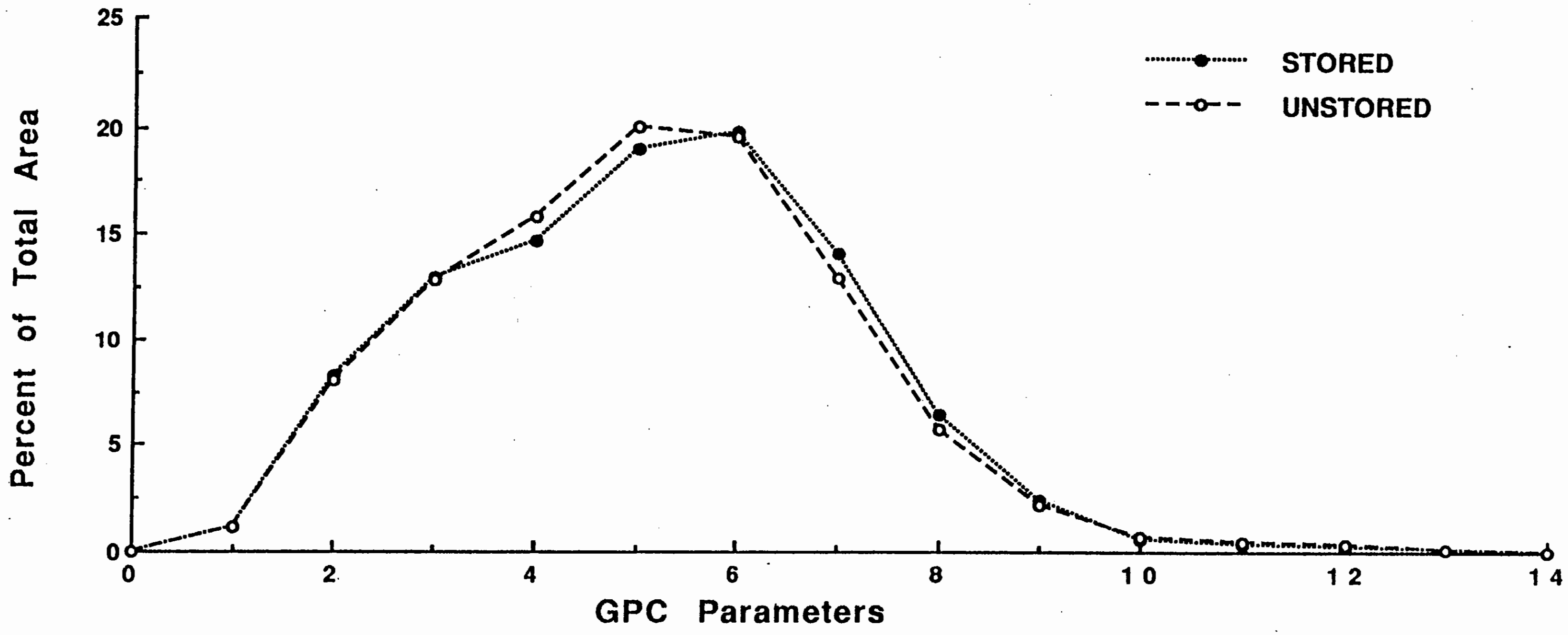


Figure 12. HP-GPC profiles for stored & unstored asphalts at plant from job 2

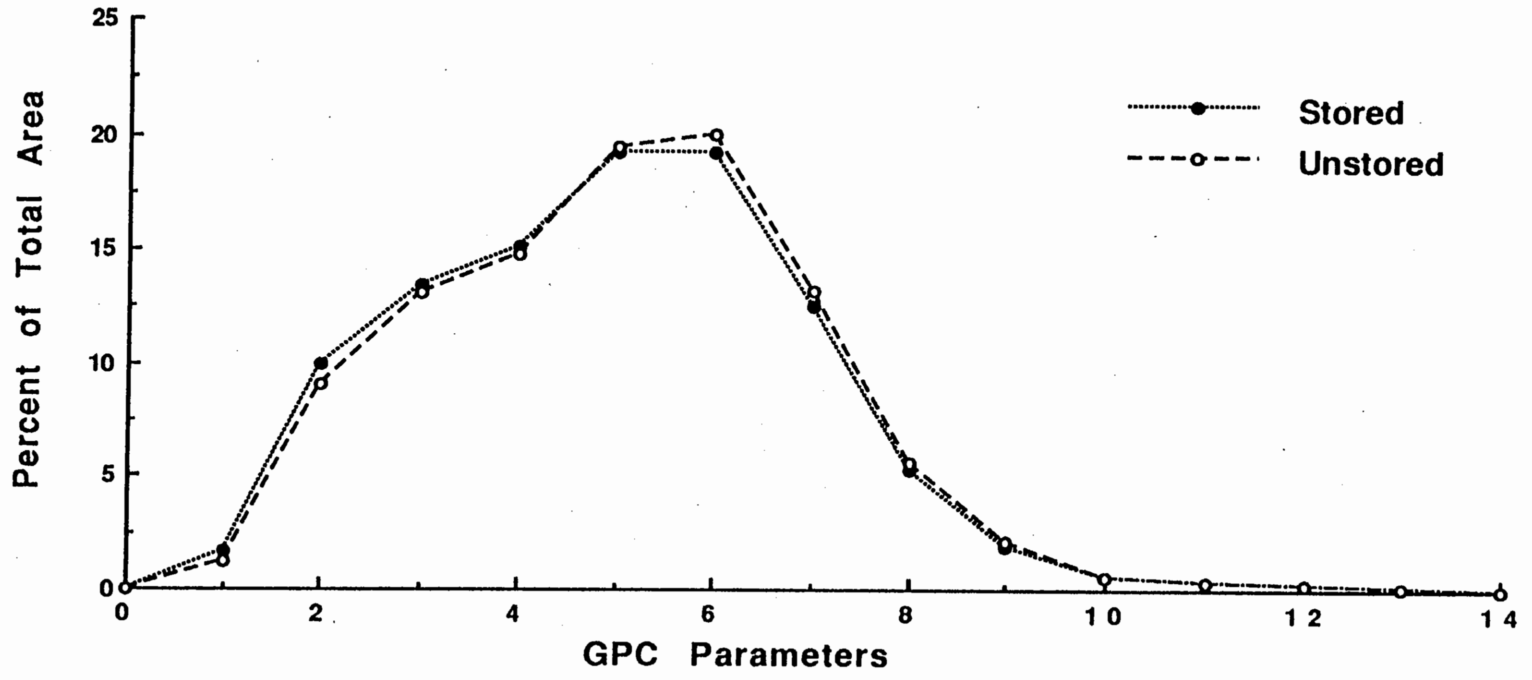


Figure 13. HP-GPC profiles for stored & unstored asphalts at plant from job 3

The profiles of the stored and the unstored asphalts sampled from trucks at the three jobs (Figures 14, 15 and 16), and after one year of service (Figures 17, 18 and 19), show that the stored asphalts have more apparent large molecules than the unstored asphalts. The differences between them, however, are small.

6.4 Analysis of Asphalt Concrete Mix Test Results

6.4.1 Analysis of Indirect Tensile Strength Results

Indirect tensile strength testing was conducted to evaluate the effect of storage on the mix properties.

Figure 20 illustrates the indirect tensile strengths for the stored and the unstored mixes from the three jobs. The figure shows that the indirect tensile strength increases from plant to site for all jobs, except for the stored mixes for job 1. For the stored mixes from job 1, the indirect tensile strength decreases from plant to site. This anomaly was also observed for the viscosity and penetration results.

The Figure also illustrates that the indirect tensile strengths of the stored mixes are higher than those of the unstored mixes. This indicates that there is some increase in indirect tensile strength due to storage. The hypothesis-test results in Table 18, however, shows that the increase in indirect tensile strength is not statistically significant at the level of 0.05.

	JOB 1	JOB II	JOB III
77°F	H_o : $M_{st}<=M_{us}$ **p*-value**=0.0548 **H_o** is Accepted at 0.05 significance level	H_o : Mst<=Mus **p*-value**=0.2077 **H_o** is Accepted at 0.05 significance level	H_o : Mst<=Mus **p*-value**=0.1244 **H_o** is Accepted at 0.05 significance level

*= Probability value. If p is less than 0.05, reject H_o; otherwise, accept H_o.

TABLE 18. HYPOTHESIS TESTS FOR INDIRECT TENSILE STRENGTHS FOR THE STORED AND THE UNSTORED MIXES AT 77°F

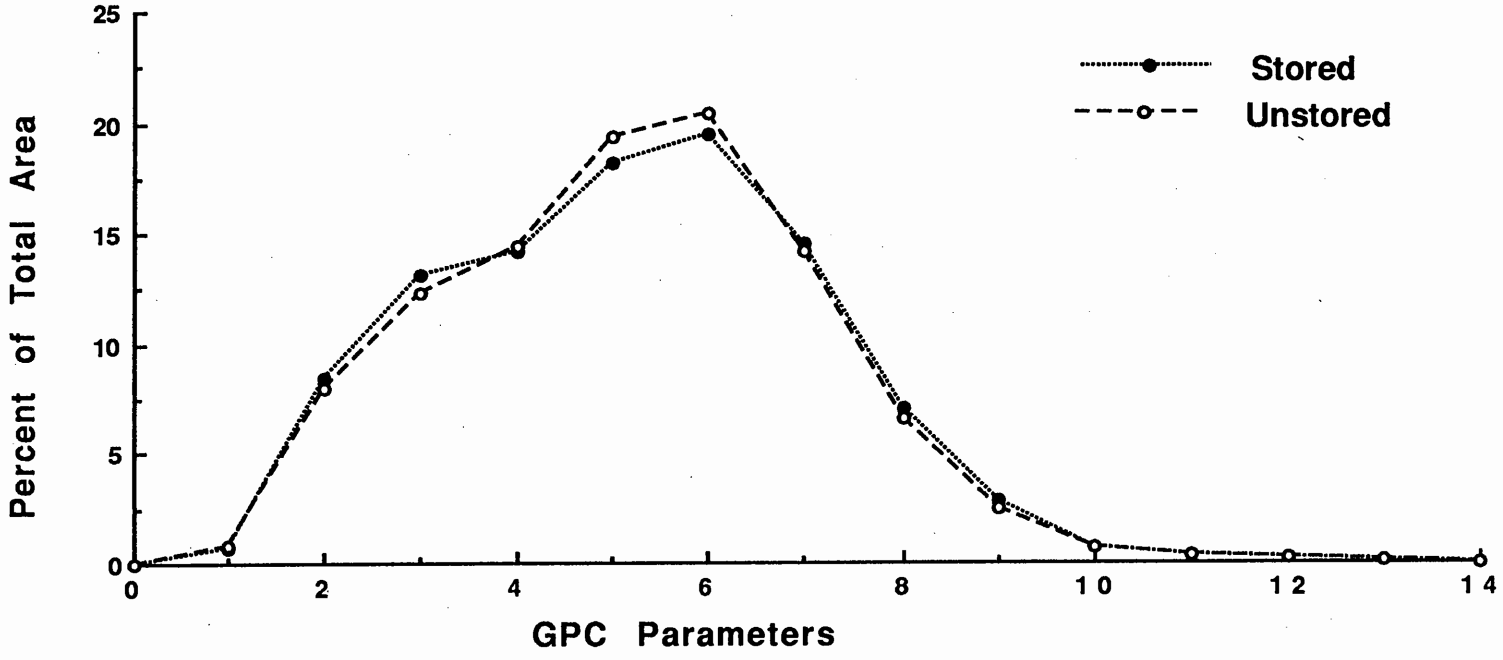


Figure 14. HP-GPC profiles for stored & unstored asphalts at site from job 1

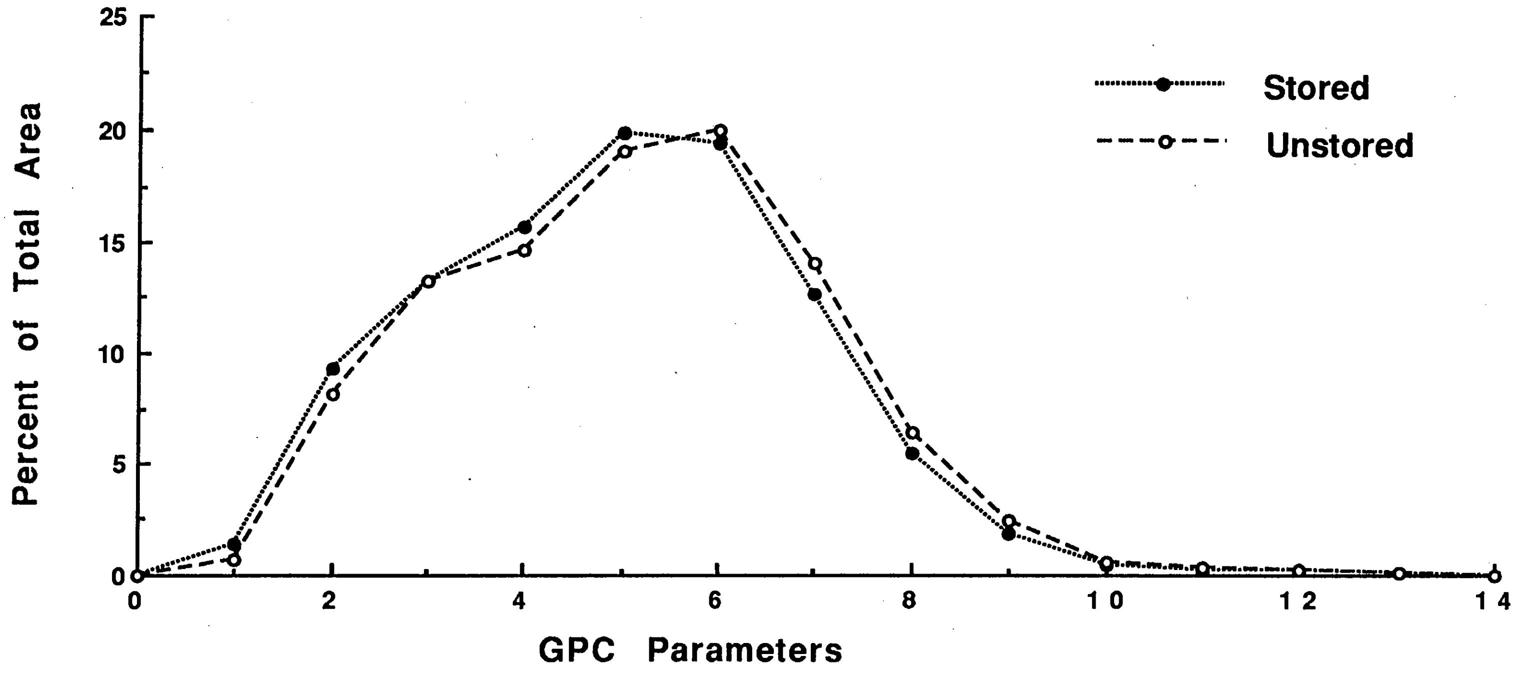


Figure 15. HP-GPC profiles for stored & unstored asphalts at site from job 2

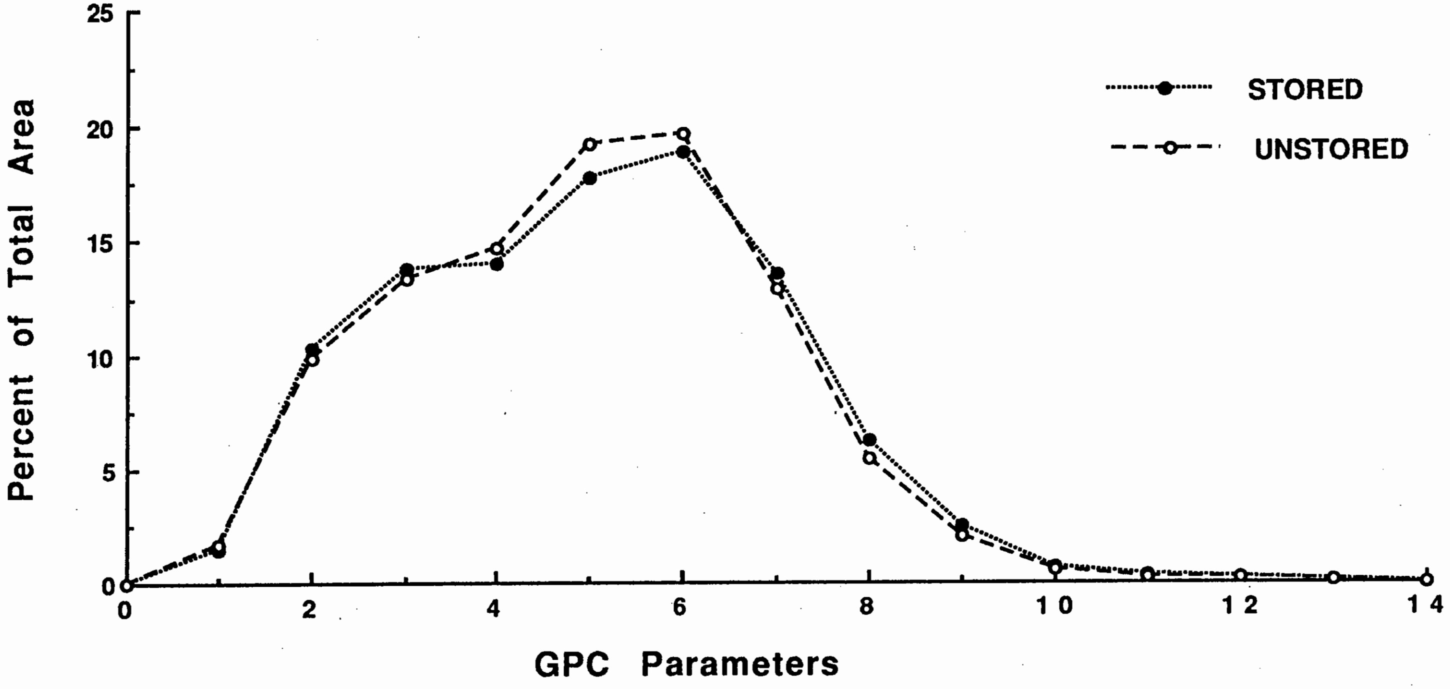


Figure 16. HP-GPC profiles for stored & unstored asphalts at site from job 3

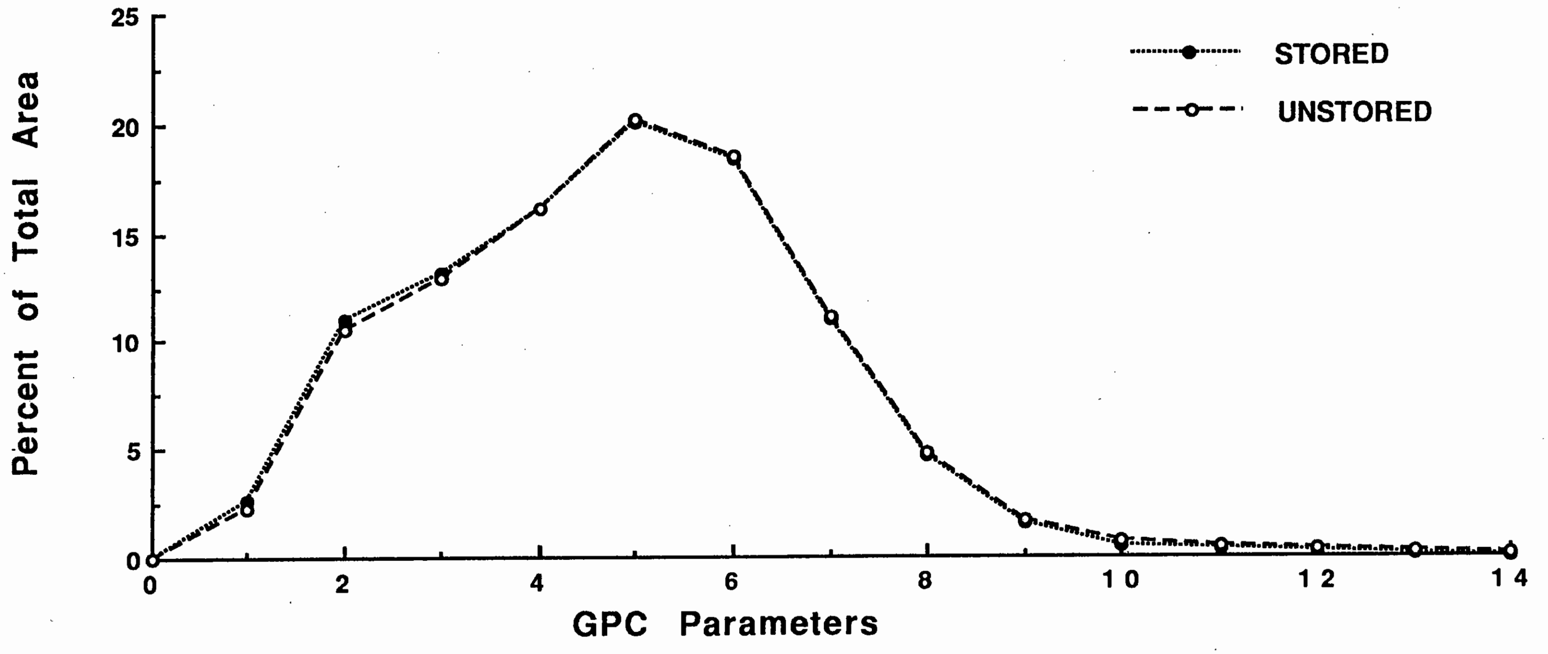


Figure 17. HP-GPC profiles stored & unstored asphlats at core from job 1

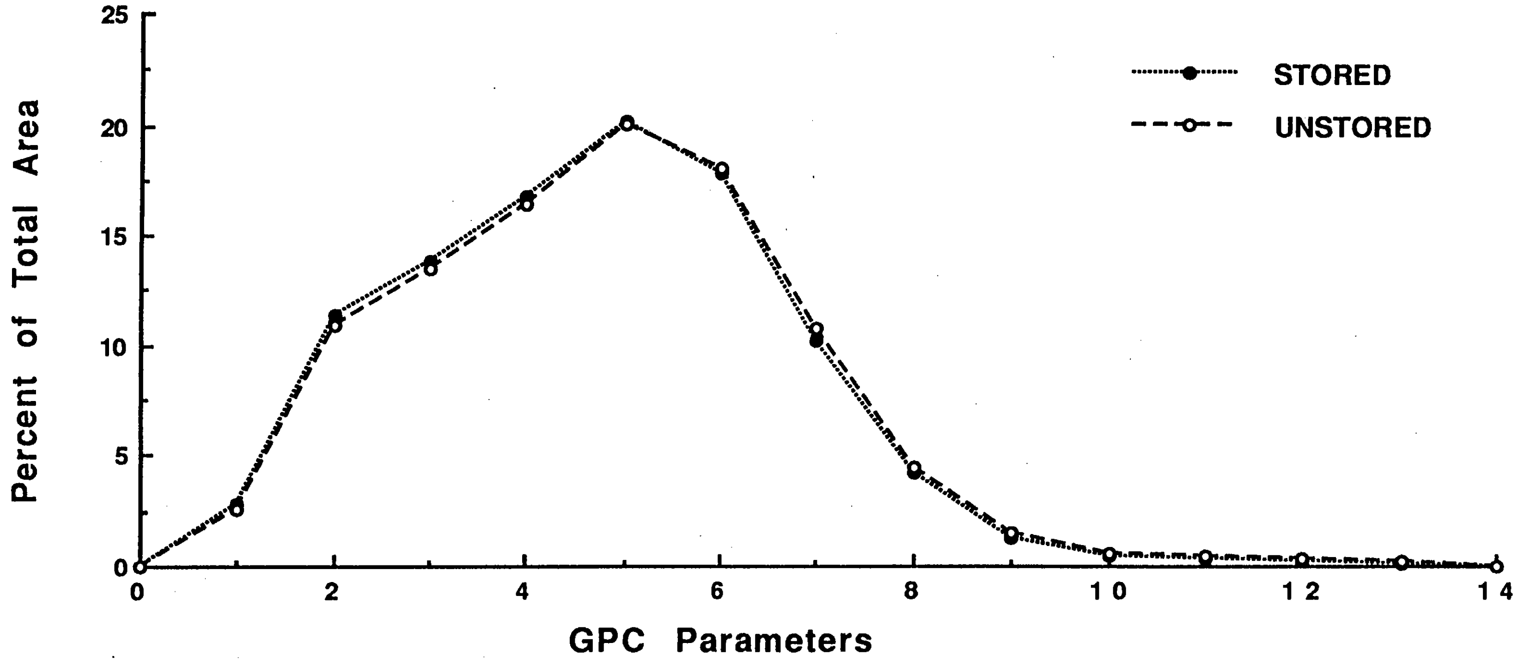


Figure 18. HP-GPC profiles for stored & unstored asphalts at core from job 2

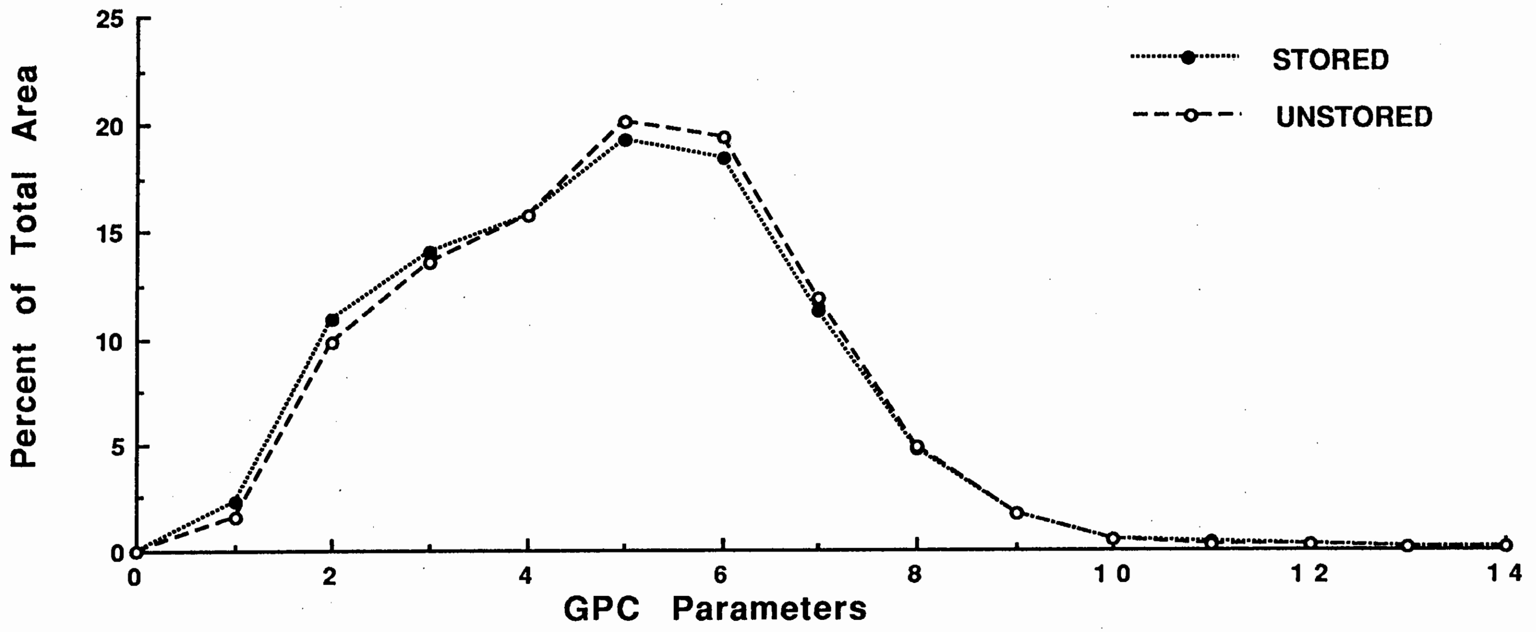


Figure 19. HP-GPC profiles for stored & unstored asphalts at core from job 3

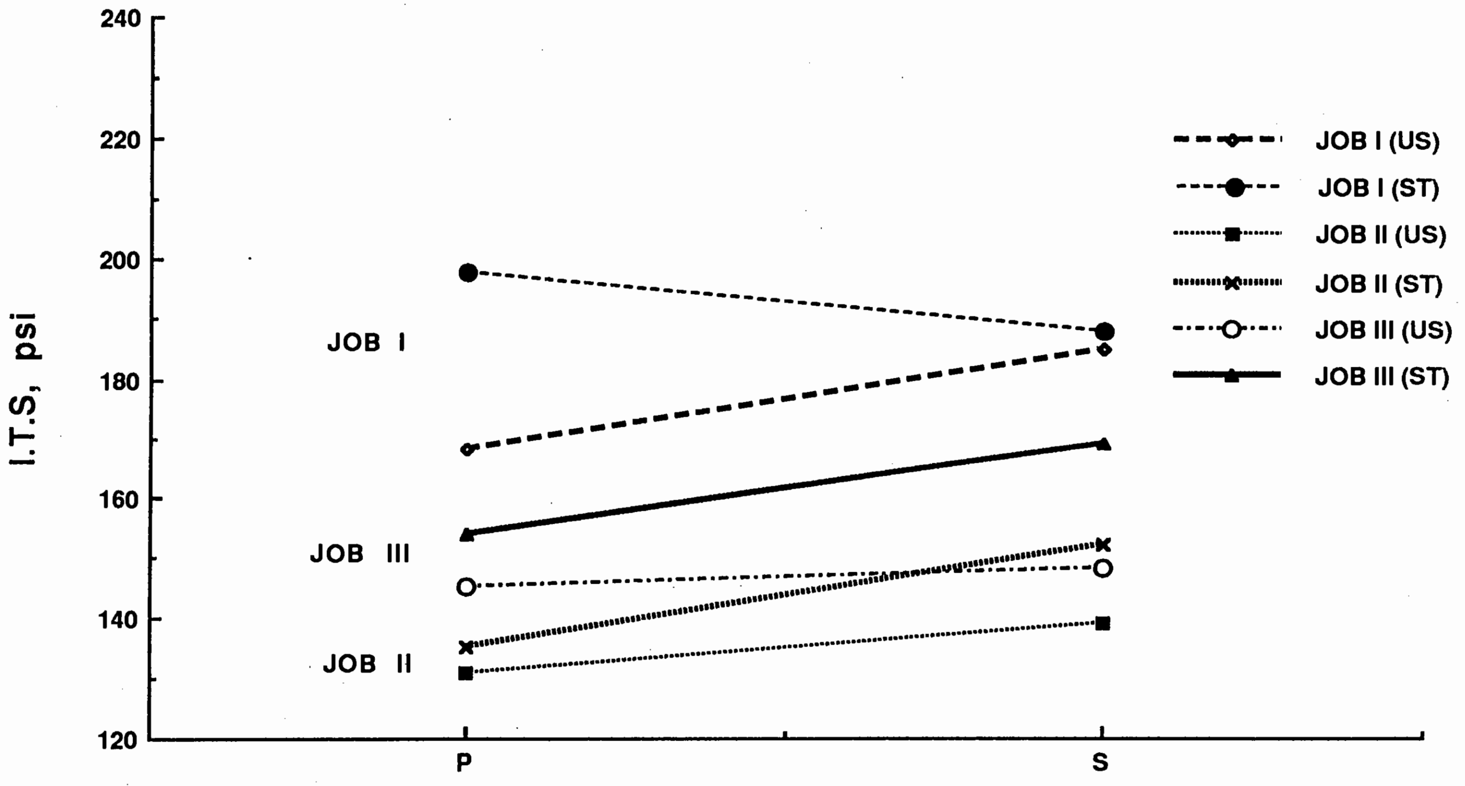


Figure 20. I.T.S. of the stored & unstored mixes at plant & site from jobs 1,2 & 3

6.4.2 Analysis of Ease of Compaction and Density Results

The ease of compaction tests were conducted to determine whether the stored mixes were harder to compact. It was deemed that this might be a problem due to the higher viscosity values of the asphalts recovered from the stored mixes sampled at all three jobs.

The analysis of variance was performed on the ease of compaction results. The null hypothesis tested in this analysis is that there are no differences between the efforts required to compact the stored and the unstored mixes. The null hypothesis was tested using an F-test at the 0.05 significance level.

The hypothesis test results presented in the Table 19 show that there are no significant differences between the efforts required to compact the stored and the unstored mixes for any of the jobs.

JOB 1	JOB II	JOB III
$H_0 : M_{st} <= M_{us}$	H_0 : Mst<=Mus	H_0 : Mst<=Mus
p*-value=0.1088	**p*-value=**0.3559	**p*-value=**0.6202
$\mathbf{H_0}$ is Accepted at 0.05 significance level	$\mathbf{H_0}$ is Accepted at 0.05 significance level	$\mathbf{H_0}$ is Accepted at 0.05 significance level

*= Probability value. If p is less than 0.05, reject H_0; otherwise, accept H_0.

TABLE 19. HYPOTHESIS TESTS FOR EASE OF COMPACTION RESULTS OF THE STORED AND THE UNSTORED MIXES

The results in the Table 13 show that the effort required to compact the mixes (both stored and unstored) from job 1 is more than the effort required to compact the mixes from jobs 2 and 3. This finding is supported by the field results, obtained at the time of laying and compacting the mixes on the roadway, which are summarized in Table 20.

The field results in Table 20 show that a greater compaction effort was needed for job 1 than for jobs 2 and 3. The density results of the cores in Table 14 show that the densities of the cores from the pavements from all three jobs were almost identical, indicating that the target density on all three jobs was similar. The results, therefore, suggest that a different compaction effort was required on each job to attain this target density for the three jobs.

	WEIGHT OF VIBRATORY ROLLER	WEIGHT OF STATIC ROLLER	NUMBER OF PASSES MADE BY VIBRATORY ROLLER	NUMBER OF PASSES MADE BY STATIC ROLLER	TEMPERATURE DURING COMPACTION
JOB I	10 TONS	-	8	-	255°F
JOB II	12 TONS	10 TONS	3	3	250°F
JOB III	12 TONS	12 TONS	2	3	255°F

TABLE 20. INFORMATION REGARDING COMPACTION EQUIPMENT

These differences in the compaction efforts required might be due to the type of the aggregate and fines used in the mixes. As mentioned before, granite gneiss and natural sand are used as the aggregate for job 1. Traprock and screened traprock fines are used as the aggregate for jobs 2 and 3.

CHAPTER 7
SUMMARY AND CONCLUSIONS

7.1 Summary

The main objectives of this investigation were: 1) to construct pavement sections for evaluating the long term effects of storage on pavement performance; and, 2) to determine the changes in asphalt and asphalt-concrete-mix properties, which may occur due to storage at elevated temperatures.

In this study, asphalt concrete mixes were sampled from three different jobs. Two sets of samples were obtained from the plant and two from the site for each job. One set of samples was from a truck loaded with material directly from the pugmill of the batch plant (the unstored mix). The other set was from a truck loaded with the material that had been stored for over 12 hours (the stored mix). At the site, the mixes were obtained from the same trucks that were sampled at the plant. The sampling was done while the trucks unloaded the mix into the paver. Cores from pavement sections constructed with the stored and the unstored mixes were also obtained after the pavements had been down for one year.

The asphalt cement properties and the properties of the mixes sampled from the three jobs were evaluated to determine the nature of the changes which resulted from hot storage.

Analysis of consistency results (viscosity and penetration) showed that there is an increase in the consistency of the asphalts due to storage. The change in consistency due to storage is more for jobs 1 and 3 than for job 2. For example, the change in viscosity at 140^{o}F due to storage is 2.3 times for job 1, 1.1 times for job 2 and 1.96 times for job 3. The increase in viscosity due to storage for jobs 1 and 3 is quite large and could possibly result in a reduction in the service life of the pavement.

Analysis of mix properties also showed that an increase in indirect tensile strength due to storage is greater for job 1 than for jobs 2 and 3. For job 2, the change in indirect tensile strength, like that for viscosity and penetration, is negligible.

The increase in consistency of the asphalts due to storage did not appear to affect the amount of effort required to compact the mixes. This is important since this result suggests that it is not necessary to modify the compaction process to accommodate the effect of storage on the mix properties. The same compaction procedure will produce a uniform density regardless of whether the mix is stored or unstored.

It was observed, however, that the indirect tensile strengths and the compaction efforts are greater for job 1 than for jobs 2 and 3. The differences in the mix properties between job 1 and jobs 2 and 3 are probably due to the fact that one type of aggregate is used for job 1, (granite gneiss and natural sand) and a second type of aggregate used for jobs 2 and 3 (traprock and traprock fines).

Two possible explanations for the differences in the performance of the mixes due to storage are the differences in the material properties for each job and the differences in storage conditions and the handling of the mixes at each job.

The asphalts used in jobs 1 and 2 were from Hudson in Providence, while the asphalt used for job 3 was from Chevron in Portland. However, the GPC results, the temperature-susceptibility results and thin-film-oven-test results suggest that all these asphalts are similar in chemical composition. Therefore, it appears that the difference in performance between the jobs is not attributable to differences in asphalt composition. On the other hand, a different aggregate was used in job 1 from that used in jobs 2 and 3. This difference might be one of the factors that explain why the effect of storage is so great for job 1. It should be noted, however, for jobs 2 and 3, the effect of storage is different even though the same aggregate is used for both.

In terms of storage conditions, most of the factors such as 1) the storage time; 2) the capacity of the silo; 3) the temperature inside the silo; and, 4) the type of atmosphere inside the silo, were similar for all three jobs. The primary difference in storage conditions between the jobs was in the type of the conveyance system used to transport the mixes from the batch plant to the silo. A slat conveyor, a drag conveyor and a bucket conveyor were used to transport the mix from batch plant to storage silo at the jobs 1, 2 and 3, respectively. The material in the slat conveyor was more exposed to the atmosphere than the material in the drag and bucket conveyor.

Since only three jobs were considered in this project, it was not possible to determine definitively the factors causing the difference in the performance of the stored material from the three jobs. Further study is needed in order to understand the effect of the various factors on the amount of change that occurs during storage.

7.2 Conclusions

The main conclusions of this study are,

1) Storage resulted in an increase in consistency of the asphalts from all jobs. The changes in job 1 and 3 are large and are likely to affect the pavement life.

2) Storage resulted in an increase in the indirect tensile strength of the mixes from all jobs.

3) Storage had no effect on the compaction effort required to compact the stored and the unstored mixes.

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