Changes Occurring in Asphalts in Drum Dryer and Batch (Pug Mill) Mixing Operations

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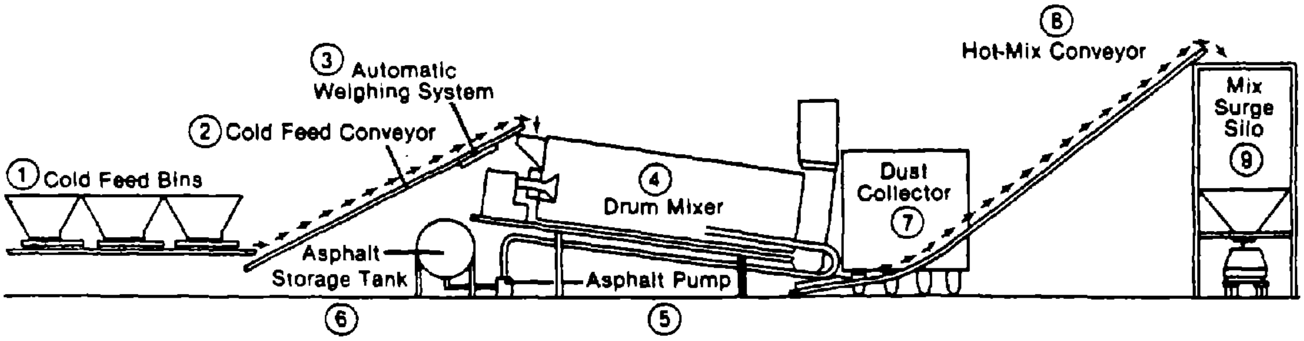

Basic Drum-Mix Plant

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

Asphalt-aggregate mixtures for pavements have been produced for many years using conventional batch (pug mill) mixing equipment. In recent years the paving industry has produced more and more asphaltic concrete mixes using drum dryer mixing procedures. Paving personnel have reported that mixes produced by the drum dryer procedure appear to have different physical properties than those mixes produced by conventional batch mixing methods. In 1985, an Federal Highway Administration staff study was begun to identify changes occurring in asphalt as it is being mixed with aggregate during drum dryer and batch (pug mill) mixing operations. The results of this study are presented in the following report.

Additional copies of the report are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, Virginia 22161.

Thomas J Pasko Jr

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Director Office of Engineering and Highway
Operations Research and Development

NOTICE

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16. Abstract

The study was designed (1) to discover whether steam distillation of asphalt takes place in a drum dryer mixer, (2) to compare changes induced by various laboratory conditioning (aging) techniques versus those occurring in drum dryer mixers, and (3) to identify possible differences in asphalts subjected to drum dryer mixing versus batch (pug mill) mixing. Fifty-five virgin asphalts were subjected to various laboratory conditioning experiments including thin film oven exposure (TFO), rolling thin film oven exposure (RTFO), (small) steam distillation (SSD), forced air distillation (FAD), and rolling forced air distillation (RFAD). Various physical and chemical properties of these conditioned samples were measured. These properties were compared with those of the residues recovered from drum dryer operations for each asphalt. By comparing the laboratory conditioned residues to the recovered residues from the drum dryer operation, similarities of the variously exposed asphalts to asphalt recovered from drum dryer mixers were ascertained. ~~This~~ demonstrated that steam distillation does not take place in drum dryer mixers. Eight matched asphalt pairs, one used in a drum dryer mix and one in a batch (pug mill) mix, were identified among 24 virgin asphalts from Georgia by statistically comparing various physical, thermal, compositional, and molecular size properties of the virgin asphalts. Asphalts were then recovered from the mixes in which each of the eight drum dryer - batch (pug mill) asphalt pairs were used. The recovered asphalts were analysed, and the results show the asphalt residues extracted from drum dryer operations to be slightly harder than those extracted from batch operations.

17. Key Words
Asphalts, Drum Dryer, Steam Distillation, Thin Film Oven Test, Rolling Thin Film Oven Test, Loose Mix

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
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

Symbol	When You Know	Multiply By	To Find	Symbol
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

Symbol	When You Know	Multiply By	To Find	Symbol
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 greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
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

Symbol	When You Know	Multiply By	To Find	Symbol
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

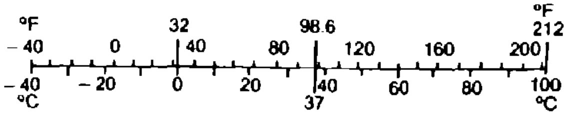
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



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* SI is the symbol for the International System of Measurement

(Revised April 1989)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

INTRODUCTION

Asphalt-aggregate mixtures for pavements have been produced for many years using conventional batch (pug mill) mixing equipment. In a batch (pug mill) plant process, heated, dried aggregate is mixed with heated asphalt in batches to obtain an asphaltic concrete mix used for paving highways. One of the most important steps in this mixing procedure is the pre-drying and heating of the aggregate to 250 to 350 °F (122 to 177 °C) before combining with asphalt to obtain the mix.(1)

In the last 20 years, a drum dryer mixing technology has been developed for obtaining pavement mixtures. In the drum dryer process, a drained but undried aggregate is continuously fed into the rotating drum mixer, flame heated from 250 to 300 °F (122 to 149 °C) and then mixed with a continuous stream of liquid asphalt to produce a mix that continuously exits at the discharge end of the mixer.(2) The main advantage of this mixing procedure is that it is a continuous mixing process that generates asphalt-aggregate mixes much faster and cheaper than using conventional pug mill mixing methods. Furthermore, aggregates do not have to be pre-dried, but only drained, before they enter the mixer.

Drum dryer mixers are now used extensively to produce mixtures for construction of asphaltic concrete pavements.

PROBLEM

In recent years the paving industry has produced more and more asphaltic concrete mixes using drum dryer mixing procedures. Paving personnel have reported that mixes produced by the drum dryer procedure appear to have different physical properties than those mixes produced by conventional batch mixing methods.(3,4) Concern has been voiced in the highway community that certain asphalts can be "steam-distilled" during hot-mix production in drum mixers.(5) Steam distillation, the distillation of an organic compound in the presence of steam, takes place when the sum of the vapor pressures of the compound and water exceeds the pressure in the distillation apparatus (in the case of a drum mixer, normally one atmosphere); the compound can then distill at a lower temperature than its normal boiling point.(6)

Some asphalt researchers have hypothesized that, in the drum dryer process, fuel oil obtained from the incomplete combustion of fuel during the time the aggregate is being flame-heated is being mixed with aggregate and asphalt causing these problems.(7) Other researchers think that a more likely occurrence would be loss of the lowest boiling point components of the asphalt by a steam distillation process. Allegedly, drum dryer mixers provide an environment in which "light ends" or low boiling materials are stripped from the asphalt by a "steam distillation" process leading to an immediate problem of possible baghouse fires and a long-term problem of poor pavement performance because of unanticipated asphalt changes during the mixing process.(5) Asphalt is hardened mostly by oxidation in thin film oven tests (TFO), a test that simulates the changes occurring to asphalts in batch (pug mill) operations.(8,9) In the steam distillation process the oxidation process is greatly reduced by the steam, so the asphalt does not harden as much as by a TFO procedure. The steam acts as a stripping gas, efficiently removing the light ends physically. If the steam distillation process does occur in drum dryer mixers, the mixers from drum dryer mixes would be less oxidized and not as hard as mixes from a batch operation.

The Florida DOT investigated the steam distillation hypothesis.(10) They constructed pavements using one aggregate and two asphalts, either steam distilled for 36 hours or not, mixed in either a drum dryer mixer or in a batch (pug mill) mixer. After 3 years, all pavements are performing well with no differences in pavement performance.

APPROACH

The Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development, recently completed a study to identify the changes occurring in asphalt as it is being mixed with aggregate during drum dryer and batch (pug mill) mixing operations. During the summer of 1985, 104 loose mixes were collected from drum dryer mix operations used for paving projects in 17 States throughout the country. Data for the mixing parameters for these mixes are in table 1. With this collection of samples, at least two distinct approaches were possible:

1. A variety of laboratory conditioning (aging) procedures, including steam distillation, could be run on virgin asphalts and these residues and

Table 1. Parameters of the mixes used in this study.

FHWA		MNF	MIX	MIX	+/-	FUEL TYPE													
			TYPE	TEMP.		A	B	C	D	E	F	G	H	I	J	%AC	%RECY	LIME?	ADD.
8509	IA	0	6.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8511	IA	0	6.1	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0
8513	IA	50	1.0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	1	0
8515	IA	50	1.0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	1	0
8517	KS	70	7.1	300	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8519	KS	37	7.1	302	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8521	KS	70	3.1	300	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8523	OH	5	4.1	270	0	0	0	0	0	0	0	0	0	0	1	6	0	0	0
8525	OH	5	4.1	310	0	0	0	1	0	0	1	0	0	0	0	5	0	0	0
8527	OH	56	3.1	300	0	0	0	1	0	0	0	0	0	0	0	8	0	0	8
8529	OH	56	5.1	244	0	0	0	0	0	0	0	0	0	1	0	3	40	0	0
8531	OH	50	4.1	250	0	0	0	0	1	0	0	0	0	0	0	3	29	0	0
8533	OH	70	4.1	290	0	0	0	0	1	0	0	0	0	0	0	6	0	0	0
8535	OH	5	9.1	285	0	0	0	0	0	0	0	0	0	1	0	5	0	0	0
8537	OH	56	3.1	270	0	1	0	1	0	0	0	0	0	0	0	5	0	0	0
8539	OH	56	4.1	305	0	0	0	1	0	0	0	0	0	0	0	5	0	0	0
8541	OH	5	3.1	295	0	0	0	1	0	0	0	0	0	0	0	5	25	0	0
8543	OH	5	3.1	320	0	0	0	1	0	0	0	0	0	0	0	4	10	0	0
8545	OH	50	3.1	300	0	1	0	1	0	0	0	0	0	0	0	3	25	0	0
8547	OH	56	9.1	295	0	0	0	0	0	0	0	0	0	1	0	5	0	0	0
8549	OH	56	5.1	275	0	0	0	0	0	0	0	0	0	1	0	4	30	0	0
8551	OH	5	4.1	315	0	0	0	1	0	0	0	0	0	0	0	6	0	0	0
8553	OH	56	4.1	275	0	0	0	1	0	0	0	0	0	0	0	6	10	0	0
8555	OH	7	4.1	280	0	0	0	1	0	0	0	0	0	0	0	5	0	0	0
8557	OH	56	4.1	300	0	0	0	0	0	0	0	1	0	0	0	7	0	0	0
8559	OH	56	5.1	280	0	0	0	0	0	0	0	0	0	1	0	4	30	0	0
8561	OH	56	5.1	300	0	0	0	0	0	0	0	0	0	1	0	2	48	0	0
8564	UT	0	1.0	290	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8566	UT	0	1.0	295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8568	NE	47	3.1	270	0	0	0	0	0	0	0	0	0	0	1	6	0	0	0
8570	NE	37	6.1	300	0	0	0	1	0	0	0	0	0	0	0	6	0	0	0
8572	NE	70	7.1	260	0	0	0	0	0	1	0	0	0	0	0	6	0	0	0
8574	NE	47	3.1	245	0	0	0	0	0	1	0	0	0	0	0	5	0	0	0

Table 1. Parameters of the mixes used in this study (continued).

FHWA		MNF	MIX	MIX	+/-	FUEL TYPE													
			TYPE	TEMP.		A	B	C	D	E	F	G	H	I	J	%AC	%RECY	LIME?	ADD.
8576	NE	70	7.1	280	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0
8586	MO	55	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8588	MO	55	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8590	MO	70	9.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8592	MO	49	7.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8594	MO	73	6.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8596	MN	6	4.1	290	0	0	0	0	0	1	0	0	0	0	0	6	0	0	0
8598	MN	0	4.1	285	0	0	0	0	1	0	0	0	0	0	0	5	0	0	0
8600	MN	50	4.1	310	0	0	0	0	0	0	1	0	0	0	0	7	0	0	0
8612	MN	50	4.1	293	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
8613	MN	6	1.0	260	0	0	0	0	0	0	1	0	0	0	0	5	0	0	0
8615	MN	58	5.1	260	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8617	ND	0	5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8619	ND	0	5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8621	ND	0	5.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8623	MN	0	1.1	280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8626	MN	0	9.1	300	0	0	0	0	0	0	0	0	0	1	0	6	0	0	0
8628	MN	50	4.1	300	0	0	0	0	0	0	1	0	0	0	0	7	0	0	0
8633	NE	37	4.1	330	0	0	1	0	0	0	0	0	0	0	0	5	0	0	0
8635	NE	47	6.1	275	0	0	0	0	0	1	0	0	0	0	0	6	0	0	0
8637	NE	37	4.1	300	0	0	0	0	0	1	0	0	0	0	0	4	0	0	0
8639	NE	37	7.1	290	0	0	1	0	0	0	0	0	0	0	0	5	0	0	0
8640	IN	89	4.1	280	20	0	0	0	0	0	0	0	0	0	0	4	0	0	0
8642	IN	67	3.1	280	20	0	0	0	0	0	0	0	0	0	0	4	0	0	0
8644	IN	5	3.1	280	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
8646	IN	3	4.1	280	20	0	0	0	0	0	0	0	0	0	0	5	0	0	0
8648	IN	5	4.1	280	20	0	0	0	0	0	0	0	0	0	0	4	0	0	0
8650	WA	0	4.1	275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8652	WA	0	5.1	320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8654	WA	85	7.1	250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
8656	WA	0	4.1	300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8658	GA	2	5.1	0	0	0	0	0	0	0	0	0	1	0	0	7	0	0	1
8660	GA	2	6.2	0	0	0	0	0	0	0	0	0	0	0	1	6	0	1	0

Table 1. Parameters of the mixes used in this study (continued).

FHWA		MNF	MIX	MIX	+/-	FUEL TYPE													
			TYPE	TEMP.		A	B	C	D	E	F	G	H	I	J	%AC	%RECY	LIME?	ADD.
8662	GA	2	4.2	0	0	0	0	1	0	0	0	0	0	0	0	5	0	1	0
8664	GA	20	5.1	0	0	0	0	0	0	0	0	0	1	0	0	7	0	0	1
8666	GA	0	4.1	0	0	0	1	1	0	0	0	0	0	0	0	6	0	1	0
8668	GA	0	4.2	0	0	0	1	0	0	0	0	0	0	0	0	6	0	1	0
8670	GA	2	9.1	300	0	0	0	0	0	0	0	0	0	1	0	6	0	1	3
8672	GA	0	4.1	0	0	0	1	0	0	0	0	0	0	0	0	6	0	1	9
8674	GA	0	3.1	290	0	0	1	0	0	0	0	0	0	0	0	6	0	1	0
8676	GA	44	3.1	0	0	0	0	0	0	0	0	0	0	1	0	6	0	1	0
8678	GA	20	3.1	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8680	GA	2	6.2	0	0	0	1	0	0	0	0	0	0	0	0	6	0	1	1
8682	GA	20	2.1	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8684	GA	2	8.2	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8686	GA	20	7.1	0	0	0	0	0	0	0	0	0	1	0	0	5	0	1	0
8688	GA	70	8.2	0	0	1	0	0	0	0	0	0	0	1	0	6	0	1	0
8690	GA	70	3.1	0	0	0	0	0	0	0	0	0	0	1	0	6	0	1	3
8692	GA	70	1.1	0	0	0	0	0	0	0	0	0	0	1	0	5	0	1	0
8694	GA	0	1.2	0	0	0	0	0	0	0	0	0	0	1	0	6	0	1	9
8696	GA	70	8.2	0	0	0	0	0	0	0	0	0	0	1	0	6	0	1	0
8698	GA	70	8.2	0	0	0	0	0	0	0	0	0	0	1	0	6	0	0	3
8700	GA	20	2.1	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8702	GA	0	4.2	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8704	GA	70	1.2	0	0	0	0	0	0	0	0	0	1	0	0	6	0	1	0
8724	SC	0	7.1	300	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
8726	SC	0	3.1	270	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
8728	SC	0	7.1	300	0	0	0	0	0	0	0	0	0	0	0	6	10	0	1
8730	SC	2	3.1	295	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0
8732	SC	0	6.1	295	0	0	0	0	0	0	0	0	0	0	0	6	0	0	2
8734	SC	0	3.1	295	0	0	0	0	0	0	0	0	0	0	0	6	0	0	2
8736	WI	50	7.1	260	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8738	WI	83	5.1	250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8740	WI	50	7.1	300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8742	WI	58	7.1	275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8744	WI	50	4.1	295	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Parameters of the mixes used in this study (continued).

FHWA	MNF	MIX	MIX	+/-	FUEL TYPE													
		TYPE	TEMP.		A	B	C	D	E	F	G	H	I	J	%AC	%RECY	LIME?	ADD.
8746 NE	37	4.1	280	0	0	0	0	0	1	0	0	0	0	0	5	0	0	0
8748 NE	37	4.1	270	0	0	1	0	0	0	0	0	0	0	0	5	0	0	0
8750 NE	37	3.1	285	0	0	0	0	0	1	0	0	0	0	0	6	0	0	0
8752 NE	47	5.1	300	0	0	0	1	0	0	0	0	0	0	0	5	0	0	0
8754 NE	37	7.1	265	0	0	1	0	0	0	0	0	0	0	0	5	0	0	0
8816 CA	46	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8818 CA	19	4.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8820 CA	69	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8827 NV	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8829 NV	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8831 NV	69	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8833 NV	41	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8835 NV	41	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8839 IL	83	7.1	295	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
8841 IL	70	3.1	295	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
8843 MI	77	0.1	310	10	0	0	0	0	0	0	0	0	0	0	6	0	0	0
8845 MI	56	0.1	305	5	0	0	0	1	0	0	0	0	0	0	6	0	0	0
8847 MI	3	0.1	292	8	0	0	0	0	0	0	0	0	0	0	6	0	0	0

MANUFACTURERS

0 = unknown
2 = Amoco Oil, Savannah
3 = Amoco Oil, Whiting, IN
5 = Ashland, Catlettsburg, KY
6 = Ashland, St. Paul, MN
7 = Ashland, Canton, OH
19 = Chevron, Richmond, CA
20 = Chevron, Pascagoula, MS
37 = Farmland, Phillipsburg, KS
41 = Goldenbear Div., Oil Dale, CA
44 = Hunt Oil, Tuscaloosa, AL
46 = Huntway Refining, Benicia, CA
47 = Husky Oil, CHeyenne, WY

Table 1. Parameters of the mixes used in this study (continued).

MANUFACTURERS (MNF)

49 = Kerr-McGee Refining, Wynnewood, OK
50 = Koch Materials, Rosemount, MN
55 = Marathon Oil, Garyville, LA
56 = Marathon Oil, Detroit, MI
58 = Murphy Oil Corp., Superior, WI
67 = Rock Island Refining, Indianapolis, IN
69 = Shell Oil, Martinez, CA
70 = Shell Oil, Wood River, IL
73 = Sinclair Oil, Tulsa, OK
77 = Standard Oil of Ohio, Toledo, OH
83 = Unocal Corp., Lemont, IL
85 = U.S. Oil & Refining, Tacoma, WA
89 = Young Refining, Laketon, IN

MIX TYPE

1.x = unknown or unusual manufacturer
2.x = AEDCO
3.x = ASTEC (AZTEC)
4.x = Barber-Greene
5.x = Boeing
6.x = Cedar Rapids
7.x = CMI (caterpillar)
8.x = H & B
9.x = Standard Havens
    if x = 0, unknown
    if x = 1, drum mixer
    if x = 2, batch mixer

MIX TEMPERATURE

Temperature (degrees F) of production mix
0 = unknown

+/- : Range of temperature.

FUEL TYPE

1: the fuel used
A: coal
B: waste/reclaimed oil
C: #2 oil/diesel

Table 1. Parameters of the mixes used in this study (continued).

FUEL TYPE

D: #4 fuel
E: #5 fuel/burner fuel
F: #6 fuel
G: gas oil
H: LP gas/propane
I: natural gas
J: other

%AC

Percent asphalt by design (mix basis)
0 = unknown

%RECY

Percent of mix from recycled pavement
0 = unknown or none

LIME?

0 = unknown or none
1 = reported to have been added

ADDITIVE (ADD)

0 = unknown or no other additives
1 = Indulin antistrip
2 = Pavebond antistrip
3 = Kling-beta LV(HM) antistrip
8 = latex/rubber
9 = unknown type

their paired asphalts recovered from drum dryer mixes characterized (vide infra). By comparing the properties of each recovered asphalt with its laboratory conditioned partner, conclusions concerning the fidelity of any given laboratory procedure to the conditions occurring in drum dryer mixers could be drawn.

2. The State of Georgia sent 24 mixes and corresponding virgin asphalts as part of this study; 11 of these mixes were from batch (pug mill) mixing procedures and 13 of them were from drum dryer operations. Here was an opportunity to use the characterization of the virgin asphalts to match mixes from the 2 types of mixing plants as using the same asphalt. Once drum dryer - batch (pug mill) pairs involving the same asphalt were identified, the characterization of the recovered asphalts of each mix pair would enable any differences between the two processes to be identified.

EXPERIMENTAL

To make the study manageable, 55 mixes and their corresponding virgin asphalts (various grades) were arbitrarily selected from various States. The asphalts were extracted and recovered from their mixes using a standard Abson method, and the recovered (REC) and virgin asphalts (VIR) were characterized (vide infra) (see appendix A, tables 14-31).(11) Asphalts from the 24 Georgia loose mixes were also extracted, recovered and characterized. The corresponding virgin asphalts used to produce these mixes were also characterized (see appendix A, tables 32-35).

The following laboratory conditioning techniques were conducted using each of the 55 virgin asphalts. The resulting residues from each procedure were characterized.

A. Conditioning Procedures

1. Thin Film Oven Exposure (TFO)(12)

This standard exposure test for asphalts involves a thin film of asphalt being exposed to air at 325 °F (163 °C) for 5 hours. The film is then collected and characterized. No evaporated materials are collected. This test simulates the effects of conventional batch mix procedures on asphalts as shown by the changes in asphalt characteristics.(9)

2. Rolling Thin Film Oven Exposure (RTFO)(13)

In this form of the standard thin film oven exposure, the asphalts are exposed at 325 °F (163 °C) to air streams in rolling bottles, coating the bottles on all inner sides with films of asphalt. It differs from the TFO exposure in its use of a smaller sample size spread over a larger area in a continuous rolling manner, allowing for a more efficient oxidation of the test asphalt in less time.

The residue asphalt is then collected and characterized. No evaporated material is collected.

3. Small Steam Distillation (SSD)(14)

This modified ASTM procedure using 75g of asphalt, not 500g, is simulating what many researchers think is the process actually occurring in the drum dryer operation.(5) Steam is bubbled through hot asphalt and removes volatile asphalt components (water-distillable light ends) from the resulting residue. The residue asphalt is then characterized. This procedure was conducted with duplicate samples.

4. Forced Air Distillation (FAD)

A laboratory distillation was developed whereby an air stream is forced over an asphalt film heated to 662 °F (350 °C) in a closed system and then bubbled through cold isooctane 32 °F (0 °C) to trap and collect any evaporated asphaltic materials (see appendix B). The asphalt residue is then characterized. This procedure is designed to simulate the TFO procedure with the added provision of catching any generated volatile materials.(12) The FAD was conducted on duplicate samples.

5. Revolving Forced Air Distillation (RFAD)

A laboratory distillation of asphalt is set up much like the FAD procedure with an air stream, but using asphalt films in a revolving container in a closed system at 325 °F (163 °C). Evaporated components are also collected in isooctane. The asphalt residue is characterized (see appendix C). This procedure was designed to simulate RTFO procedures with the provision of catching any generated volatile materials. The RFAD was conducted on duplicate samples.(13)

B. Analytical Procedures

Various analytical laboratory test procedures were used to ascertain any like attributes or departures of such in the laboratory comparisons of asphalts and asphaltic residues. These consisted of physical properties (penetration and viscosity), thermal properties (differential thermal analysis), functional group composition (infrared analysis), and molecular size distribution (gel permeation chromatography). The resulting data permitted a differentiation among the residues from various exposures and a characterization of the changes occurring both physically and chemically in the asphalts during conditioning. The data were also used to identify the identical Georgia virgin asphalts and the differences between recovered asphalts from batch and drum dryer mixes of like Georgia virgin asphalts.

1. Penetrations (Pen)

Penetrations of virgin asphalts, asphalts recovered from mixes, and residues from various laboratory conditioning experiments were obtained at 85, 77, 60, and 50 °F (29, 25, 16, and 10 °C) following the procedures described in AASHTO T49.(15) All penetrations at various temperatures used the time and weight specified for the penetration at 77 °F (25 °C).

2. Viscosities (Vis)

The procedures in AASHTO T201 and T202 were used to conduct the kinematic viscosities at 275 °F (135 °C) and the absolute viscosities at 140 °F (60 °C) of virgin asphalts, asphalts recovered from mixes, and residues from various laboratory conditioning experiments.(15)

3. Differential Thermal Analysis (DTA)

Differential thermal analyses were conducted using a Perkin-Elmer System 4 Controller and DTA 1700 Differential Thermal Analyzer. In this procedure asphalts were heated in air and the energy of reaction or structure change measured. Approximately 3 mg of sample were used, and the samples were prepared and run according to manufacturer's recommended procedures. Scans were made ranging from 212 to 1112 °F (100 to 600 °C) at a heating rate of 9 °F/min (5 °C/min). Typical thermograms as illustrated in figure 1 were obtained. The data consisted of determining a ratio of two areas of the thermogram produced by dropping a perpendicular from the point of lowest exothermic energy between 572 to 752 °F (300 to 400 °C) to the baseline, calculating the areas of the resulting peaks 1 and 2 by individual peak weight measurements, and taking the ratio of these areas (P1/P2). The temperature of the maximum of peak 2 (Tpk2) was read directly from each thermogram. Tpk2 was used because only Tpk2, not Tpk1, showed appreciable variation from asphalt to asphalt.

4. Infrared Spectroscopy

a. Sample preparation and spectra scan (IR).

All organic materials absorb infrared (heat) radiation at various energies, e.g., in units of cm^{-1}, according to their molecular structure, in particular, their functional group composition. In this procedure, infrared radiation was directed through asphaltic films. Absorbed radiation was measured by a detector and the infrared spectra (plot of infrared radiation absorbed vs energy) were produced (figure 2). The infrared spectra were obtained using a Nicolet 390 FTIR Spectrometer. Asphalt was applied as a film to a KBr plate with a spatula containing the hot asphaltic material. Sample scans were then obtained, and the asphalt film thickness adjusted so the peak at 2926.6 cm^{-1} fell between 10 to 20 percent transmittance (0.7 to 1.0 absorbance units). Ten scans of the same sample were then taken and averaged.

b. Interpretation of infrared spectra.

The infrared spectra were analyzed in terms of the relative areas under peaks in different energy regions of the spectrum. Peak areas are roughly

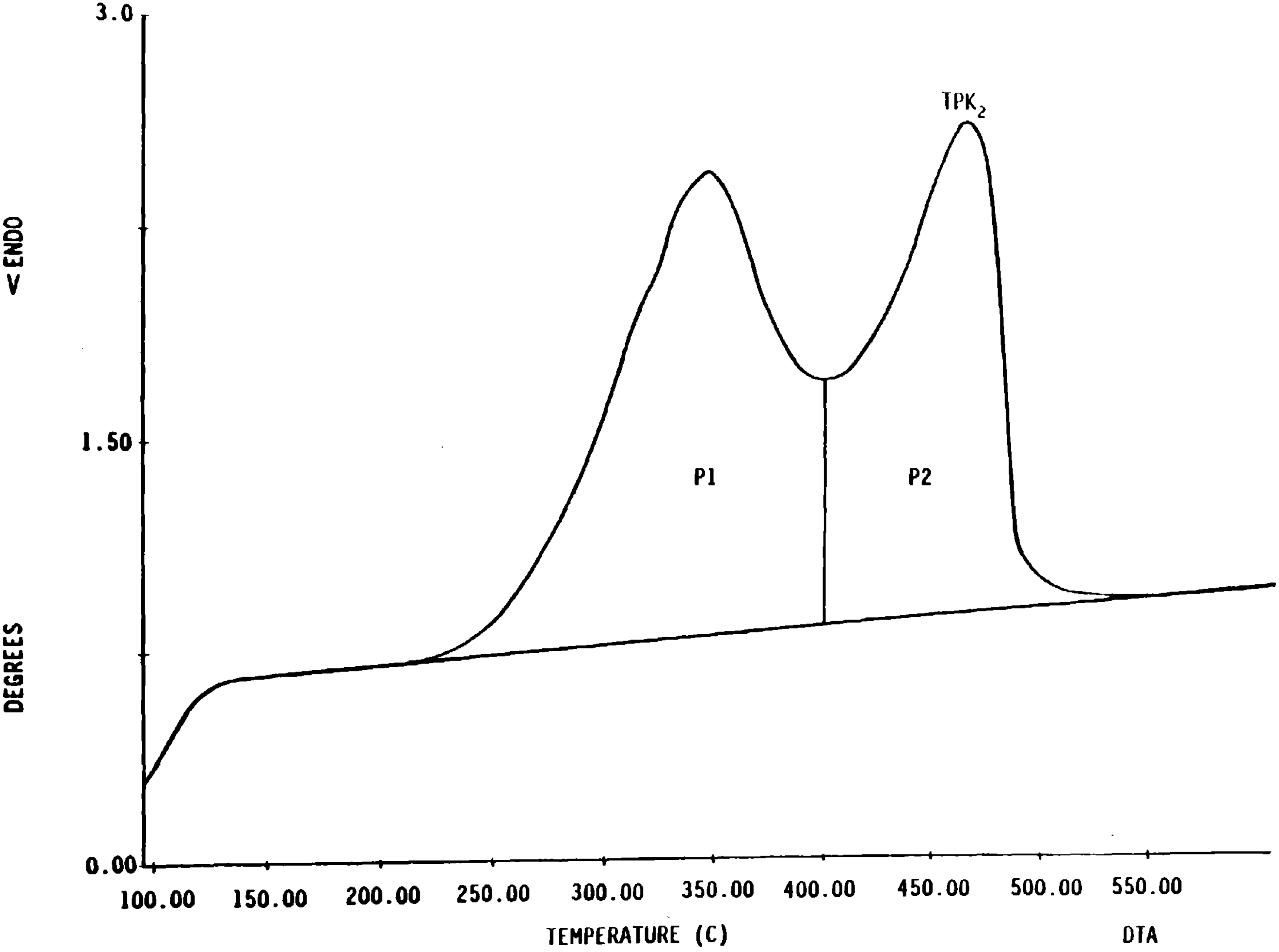

Figure 1. Differential thermogram of an asphalt.

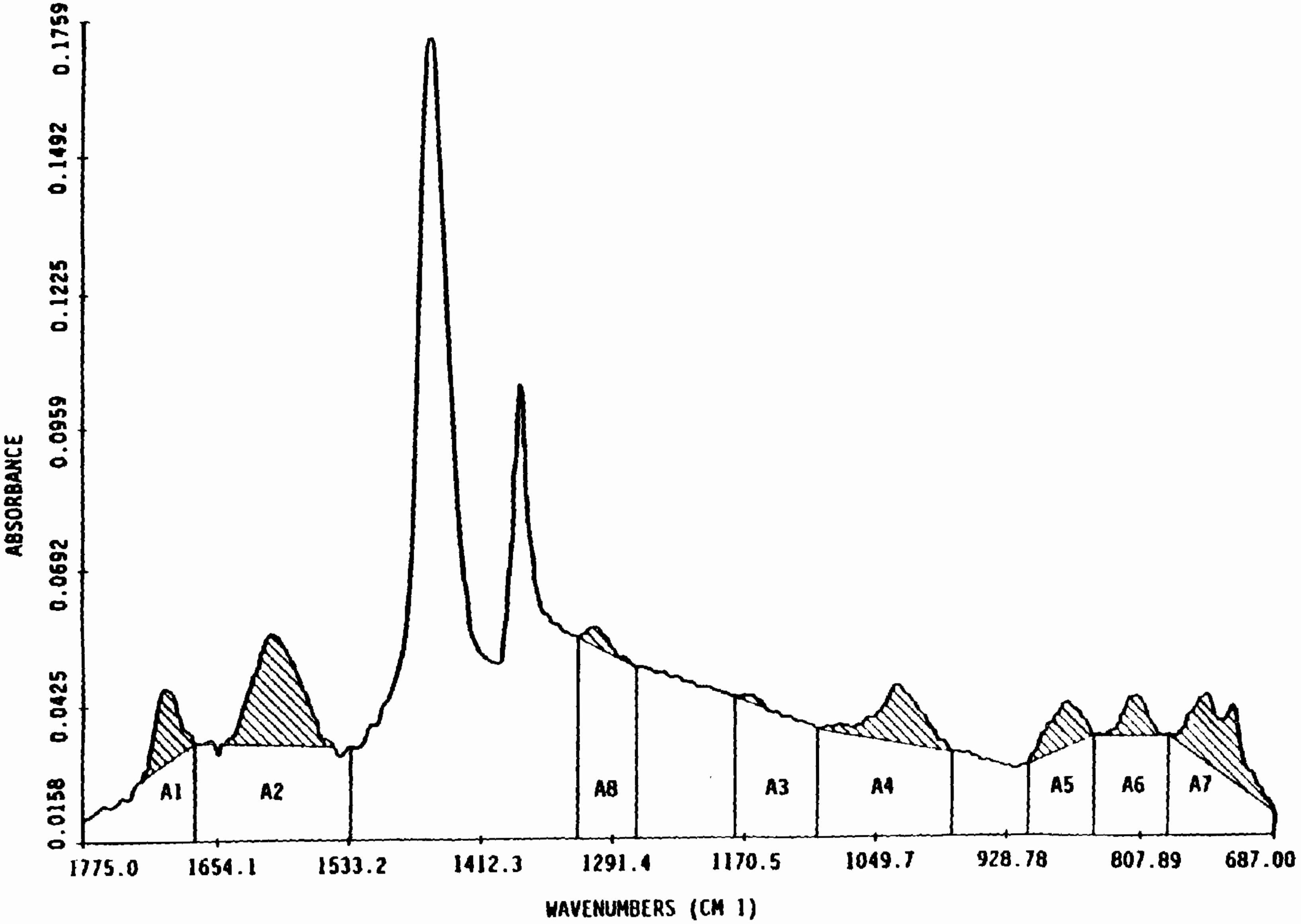

Figure 2. Infrared spectrum of an asphalt.

proportional to concentration for a given chemical molarity. Most differences in peak area values of radiation absorption between the virgin and recovered or laboratory conditioned asphalts were found in table 2.

A computer program was prepared using procedures developed by David Stokes, Delaware Department of transportation, to integrate peaks in each of the above regions (a_n) for each spectrum and to obtain a ratio of the peak area of each of the above regions over the total area (a_n/a_T) of those eight regions.

Spectra were taken of all 55 virgin asphalts, recovered asphalts from 55 mixes, and duplicate residues from the following laboratory conditionings: TFO, FAD, RFAD, RTFO, and SSD.

5. High Pressure Gel Permeation Chromatography (HP-GPC)

A high pressure gel permeation chromatograph (Waters Associates) with three Ultrastyragel columns (Waters 1000 °A, 500 °A, and 100 °A) connected in series and a UV absorption detector (Schoeffel 700) at 340 nm was used in this study. The data were calculated according to published procedures by P.W. Jennings and reported as percent large molecular size (LMS), medium molecular size (MMS), and small molecular size (SMS) particles in each asphalt (figure 3) (see appendix D).(18)

C. Repeatability and Available Reproducibility of the Various Laboratory Methods Employed in this Study.

The penetrations at 77 °F (25 °C), vacuum capillary viscosities at 140 °F (60 °C), the kinematic viscosities at 275 °F (135 °C), the Thin Film Oven Tests (TFO), the Rolling Thin Film Oven Tests (RTFO), and Abson recoveries of the asphalt from submitted mixtures were carried out in FHWA laboratories in accordance with the standardized test procedures bearing AASHTO and ASTM designations.(11,12,13,15)

All of these procedures have accompanying precision statements which point out statistically the reliability of measurements obtained with them. Table 3 presents a synopsis of these statistical statements which the FHWA

Table 2. Eight spectral regions of an asphalt.

Area	Region, cm^{-1}	Assignments[16,17]
1	1775 to 1670	C=O (Carbonyl Stretch)
2	1670 to 1532	Unsaturated C=O, C=C (Olefinic Stretch)
3	1180 to 1113	Secondary & Tertiary C-O, S=O
4	1113 to 983	Primary C-O, S=O
5	917 to 843	Polysubstituted Aromatic
6	843 to 785	Aromatic
7	785 to 687	Monosubstituted Aromatic C-H
8	1325 to 1281	Aromatic amine C-N or oxidized Nitrogen N-O

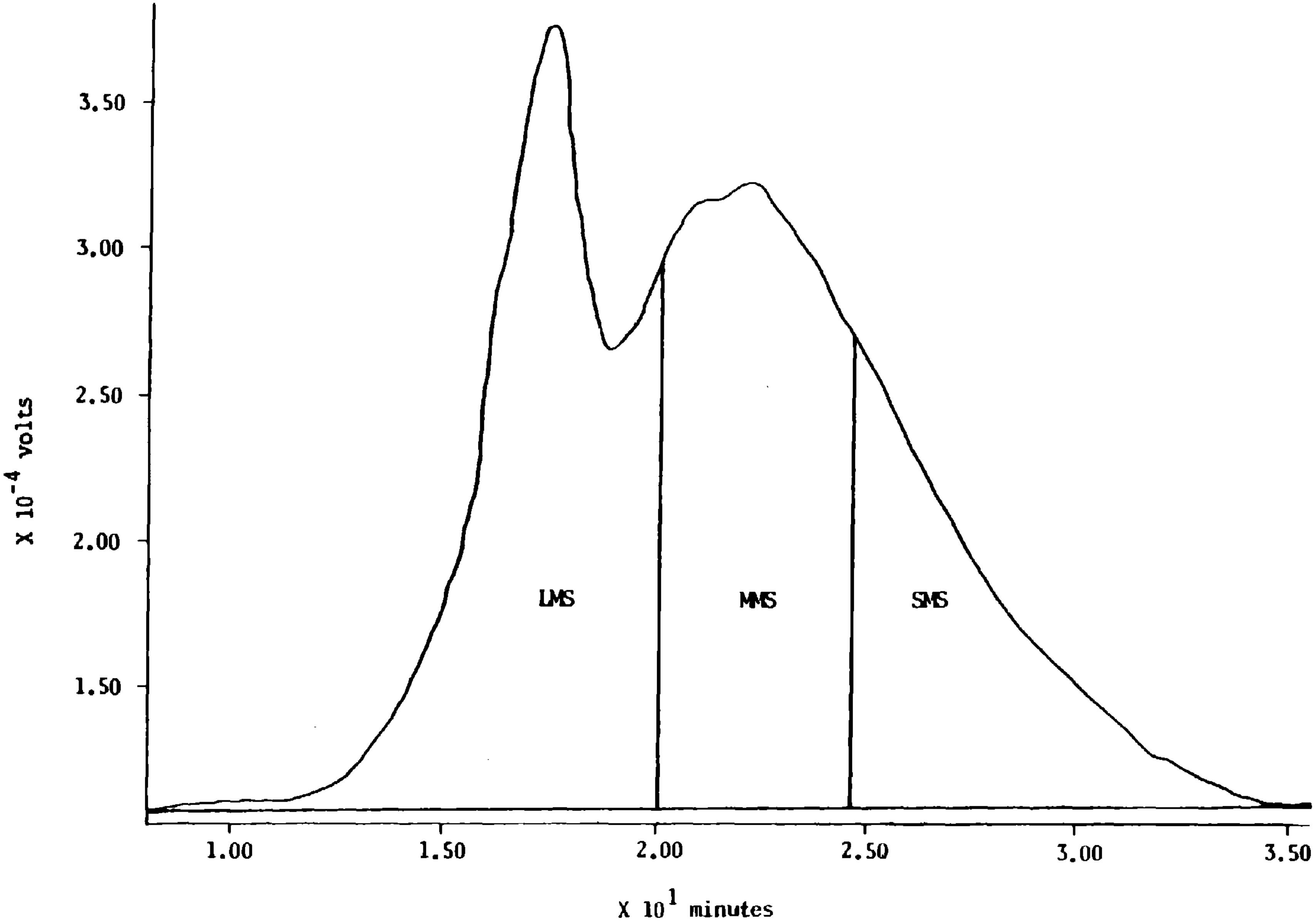

Figure 3. A high pressure gel permeation chromatogram of an asphalt.

Table 3. Repeatability of penetration, viscosity, TFO exposure, RTFO exposure, and Abson recovery tests.[1]

	AASHTO Design	ASTM Design	Repeatability
Penetration 25 °C	T-49	D-5	Pen<50 = 1dmm
Vacuum Capillary Viscosity at 60 °C	T-202	T-2171	7% of mean
Kinematic Viscosity (KV) at 135 °C	T-201	D-2170	1.8% of mean
Thin Film Oven Test Residue[2]	T-179	T-1754	16.0% of mean
Rolling Thin Film Oven Exposure	T-240	D-2872	6.5%[3] of mean
Abson Recovery[4]	T-170	D-1856	Pen SD[5]= 1.84 dmm

[1] Criteria to be used for judging the acceptability of results (95% probability).

[2] Applicable to asphalt cements having viscosity ratios,

$$\frac{\text{Vis. at 140 °F after test}}{\text{Vis. at 140 °F before test}}$$

[3] Viscosity results of 2 measurements after test by same operator not differing by more than 6.5 percent of the average.

[4] Based on 8 samples, tested in duplicate by 4 laboratories in 1971.

[5] Within laboratory standard deviations.

helped to establish statistically with round robin laboratory tests of asphalt and which have proven to satisfactorily evaluate asphalt test results.

In laboratory comparison using our IR, DTA, and GPC approaches there were no precision statements readily available. So, the researchers were compelled to derive the precision for the analytical and comparative approaches. Six asphalts were picked at random from the supply. IR, DTA, and GPC analyses and comparison were performed on three replicates of each of the six selectees from IR and DTA and on two replicates of each for GPC. Using these data, the standard deviation of these test methods was calculated (table 4).(26) Appendix E, procedure 2, discusses the calculations in detail to obtain these precision measurements and the ways they were used in this paper. There were also no standard test procedures for the FAD, RFAD, or SSD tests run in FHWA laboratories, although procedures in ASTM D-255 for SSD was followed modified only by using 75g asphalt, not 500g.(14) Two tests were conducted and two residues were obtained for each of these procedures. Data for penetration at 77 °F, viscosities at 140 and 275 °F, and differential thermal analysis were obtained. A Student's paired test (appendix E, procedure 4) showed that the asphaltic residues afforded by both tests using each procedure were not significantly different for those four parameters. Since these sample residues from both tests were the same, IR and GPC data were collected only for the residues from the first test for each procedure. Data from the first test for each procedure were used in all calculations in this report.

RESULTS

A. Comparisons of Laboratory Exposure Residues with Extracted Drum Dryer Mix Residues.

For valid comparisons of the effects of laboratory aging versus drum dryer mixing on asphalt, the analytical data were manipulated to put the comparisons on a common basis. Tables 5 and 6 show the results of these manipulations. For example, different asphalts have different initial (virgin) penetrations and viscosities. In order to compare changes in penetration or viscosity that different asphalts undergo upon exposure to a given conditioning or mixing procedure, the penetration (or viscosity) of the recovered asphalt (REC) for example is divided by the penetration (or

Table 4. Standard deviations[1] of the ratio of peak areas (P_1/P_2) and Tpk_2 of differential thermal analysis (DTA); the large, medium, and small size components of HP-GPC; and each of eight specific areas[2] of the infrared scan.

Area #	1	2	3	4	5	6	7	8
	0.0072	0.0167	0.0129	0.0439	0.0153	0.0060	0.0347	0.0058

DTA : Ratio of peak areas $(P_1/P_{2)}$ = 0.05

Maximum temperature at second peak (Tpk_2) = 1.19 °C

GPC: Large Molecular Size (LMS) = 0.714

Medium Molecular Size (MMS) = 0.969

Small Molecular Size (SMS) = 0.740

[1] Standard deviations were calculated by the 2nd procedure in appendix E.

[2] Infrared areas were calculated by computer as describe on page 9 of this report.

Table 5. Physical, thermal, and molecular size parameter ratios. Averages (Avg) and standard deviations (SD) of asphalts from drum dryer mixes and laboratory conditioned asphalts were compared with the virgin asphalts.

		REC/VIR	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
Pen 77 °F	Avg	0.45	0.60	0.48	0.81	0.51	0.82
	SD	0.26	0.06	0.06	0.41	0.06	0.08
Vis 140 °F	Avg	7.45	2.56	3.45	4.10	3.45	1.35
	SD	2.49	7.20	0.62	6.26	1.60	0.26
Vis 275 °F	Avg	2.11	1.49	1.57	1.66	1.55	1.18
	SD	0.54	0.15	0.13	1.32	0.19	0.13
VTS(18)	Avg	1.02	1.01	1.03	1.02	1.01	0.99
	SD	0.04	0.03	0.03	0.08	0.04	0.03
PVN_{140}(19)	Avg	0.03	0.92	0.79	0.46	0.65	0.71
	SD	2.05	1.75	0.62	1.55	0.79	1.31
P1/P2	Avg	1.00	1.12	1.03	1.06	1.04	1.10
	SD	0.23	0.17	0.24	0.13	0.17	0.14
Tpk2	Avg	1.00	1.00	0.96	1.00	0.99	1.00
	SD	0.02	0.01	0.19	0.01	0.01	0.01
LMS	Avg	1.43	1.25	1.24	0.95	1.31	0.99
	SD	0.49	0.23	0.14	0.14	0.31	0.09
SMS	Avg	0.87	0.93	0.93	1.02	0.92	1.01
	SD	0.07	0.04	0.09	0.08	0.05	0.05

Table 6. Infrared area ratios for eight areas. Averages (Avg) and standard deviations (SD) for asphalts from drum dryer mixes and laboratory conditioned asphalts were compared with the virgin asphalts.

IR Area No.		REC/VIR	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
1 (C=O)	Avg	-1.96	1.74	0.56	-0.27	0.62	3.83
	SD	11.58	6.52	0.94	3.38	3.78	18.92
2 (Unsat C=O)	Avg	0.80	0.92	1.10	1.08	0.99	1.03
	SD	0.22	0.47	0.17	0.09	0.30	0.26
3 (Tert. C-O)	Avg	-0.53	1.76	1.16	1.33	3.07	5.41
	SD	5.18	4.97	1.98	2.54	9.40	17.63
4 (Prim. C-O)	Avg	2.82	1.74	1.48	0.91	1.54	0.79
	SD	3.86	1.41	0.87	0.66	3.39	1.22
5 (Polysub Ar)	Avg	1.01	1.27	1.01	1.02	1.40	1.52
	SD	0.50	0.51	0.16	0.11	0.66	0.71
6 (Aromatic)	Avg	0.76	0.96	1.08	1.03	0.97	1.10
	SD	0.18	0.13	0.21	0.14	0.25	0.18
7 (Monosub Ar)	Avg	0.71	0.84	0.76	0.93	0.87	0.97
	SD	0.20	0.28	0.36	0.11	0.28	0.16
8 (Ar Nitrog, C-N or N-O)	Avg	0.75	1.05	1.05	1.00	1.01	1.15
	SD	0.20	0.20	0.17	0.22	0.30	0.21

viscosity) of the virgin asphalt (VIR). If there is no change in an asphalt upon conditioning, REC/VIR = 1. If the asphalt hardens upon conditioning, as is typical, the penetration comparison is REC/VIR < 1 and the viscosity comparison, REC/VIR > 1. This ratio treatment was used for all analytical and derived parameters and for all types of conditioning used. Tables 5 and 6 report the average value of these ratios (with outliers omitted) (see appendix E, procedure 5) for 55 asphalts, and their standard deviations (SD).

From an examination of table 4 it may be seen that both of the DTA parameters, P1/P2 and Tpk2, show negligible change in the asphalts regardless of whether they are recovered from a drum dryer mix or have undergone any of the five laboratory aging procedures. Both the ratio of the two DTA peak areas (P1/P2) and the maximum temperature of the second peak (Tpk2) have values quite close to one. Similarly, the viscosity temperature susceptibility (VTS) ratios show virtually no change from unity.(19)

To decide whether steam distillation is occurring in drum dryer mixing, the ratios for the five laboratory aging procedures are compared with the ratio for the asphalt recovered from drum dryer mix (REC/VIR). For viscosities at 140 °F (60 °C) and 275 °F (135 °C), the ratio for the (small scale) steam distillation (SSD/VIR) deviates more from the ratio REC/VIR than do the ratios for any of the other four laboratory aging procedures (TFO, RTFO, FAD, and RFAD). The HP-GPC and penetration data are not quite so clear cut. The LMS and penetration at 77 °F parameters for SSD/VIR are unlike that for the drum dryer mix (REC/VIR) and three out of the four other laboratory aging techniques. Only FAD/VIR has a value near that of SSD/VIR. The SMS parameter gives similar ratios for all laboratory aging procedures, which are slightly higher than that of REC/VIR. The errors associated with the PVN data are very large, leading to difficulty in a clear explanation of these results.(20)

Laboratory treatment SSD is a steam distillation of the virgin asphalts according to ASTM D-255, "Steam Distillation of Bituminous Protective Coatings."(14) Its residues appear to be most unlike the asphalts recovered from drum dryer mixtures than any of the other four laboratory treatments. This comparison negates claims of a steam distillation of light ends affecting adversely the quality of drum dryer mixtures.(5)

In table 6 the infrared (IR) spectroscopy parameters are handled by ratioing the infrared area ratios for the drum dryer mix recovered asphalt or laboratory aged asphalt to that for the virgin asphalt. Thus the IR data is handled just like the data recorded in table 5. Steam Distillation, SSD/VIR, deviates more from the asphalt recovered from the mix (REC/VIR) than all the other laboratory aging procedures for all of the IR peaks except peak 2. SSD/VIR is different from REC/VIR, but not different from the ratios of at least some of the other laboratory aging procedures for peaks: 2, 4, 5, 6, and 7.

The above procedures, while generally convincing that the effects of drum dryer mixing on asphalt are less like steam distillation than any of the other laboratory aging techniques considered, are not statistically based. Table 6 shows the results of the Student's paired t-test comparing parameter ratios of asphalts extracted from drum dryer mixes/virgin asphalts to residues of like virgin asphalts aged according to the various laboratory procedures/virgin asphalts (see appendix E, procedure 4).(21) For any given parameter, e.g., penetration, the null hypothesis is that the mean of that parameter ratio for an asphalt recovered from a mix is the same as the mean of that parameter ratio for an asphalt subjected to each of the laboratory conditioning (aging) procedures. If the value of t exceeds the critical value which is determined by the number of degrees of freedom (essentially the amount of data) and by the confidence level sought, then the null hypothesis is wrong and the asphalt recovered from the mix is different from an identical asphalt subject to the particular laboratory conditioning procedure.

The t statistic (table 7) shows that 2 out of the 17 parameters are not significantly different for the steam distillation (SSD/VIR) as compared to the drum dryer mixer recovered asphalt (REC/VIR). This is a smaller number of parameters of similarity than for any of the other four laboratory aging procedures. The next most different procedure is the TFO with four similar parameters, followed by RTFO with five similar parameters, than by the RFAD with seven and the FAD with eight similar parameters.

Table 7. Student's paired t-test(21) of various parameters for recovered asphalts vs laboratory residues.[++]

	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
Pen 77 °F	-4.647***	1.161 NS	-3.355**	-1.754 NS	-10.611***
Vis 140 °F	5.060***	2.331*	0.425 NS	3.884 NS	6.273***
Vis 275 °F	8.382***	4.288***	0.723 NS	3.156**	12.655***
VTS	2.466**	-2.318**	-0.031 NS	0.548 NS	4.953***
PVN$_{140}$	-1.845 NS	-4.835***	-0.933 NS	-2.089**	-2.073**
P1/P2	-2.763**	-0.570 NS	-1.472 NS	0.149 NS	-2.863**
Tpk2	-1.129 NS	1.068 NS	-1.986 NS	0.054 NS	-1.269 NS
LMS	2.914***	3.784***	9.193***	3.080***	7.013***
SMS	-5.749***	-5.554***	-9.160***	-5.083***	-13.639***
A1	-1.680 NS	-1.458 NS	-1.326 NS	-0.947 NS	-0.977 NS
A2	-2.580**	-5.890***	-10.242***	-5.878***	-7.221***
A3	-1.804 NS	-2.509*	-1.818 NS	-1.719 NS	-1.989**
A4	2.743***	5.548***	5.446***	6.955***	4.770***
A5	-4.443***	-4.805***	-8.961***	-4.016***	-7.975***
A6	-6.151***	-7.767***	-11.414***	-6.125***	-10.875***
A7	-3.508***	0.235 NS	-4.935***	-5.012***	-9.618***
A8	-9.109***	-7.930***	-4.076***	-6.689***	-12.599***

NS = Not Significant.

* = Significant at 95% probability level.

** = Significant at 99% probability level.

*** = Significant at 99.9% probability level.

[++] = The number of samples used to calculate t for the various ratio comparisons varied from 17 to 55, according to the test performed (see appendix A).

B. Comparisons of Georgia Asphalts Processed in Drum Dryer Mixers Versus in Batch (Pug Mill) Plants.

Because Georgia sent 11 mixes and corresponding virgin asphalts from batch (pug mill) plants in addition to the 13 from drum dryer mixers, the opportunity existed to possibly compare the 2 mixing processes. It was possible, or even likely, that among the 24 Georgia asphalts, there were instances where the same asphalt was used in both a drum dryer mixer and in a batch plant. One could look for this by characterizing the accompanying virgin asphalts and looking for drum dryer mixer - batch plant pairs. Upon identifying such pairs, if indeed any existed, the asphalt binders recovered from their associated mixes could be characterized and any differences between asphalts processed in a drum dryer mixer and in a batch plant could be determined.

It was assumed that asphalt pairs, if they existed, would be produced by the same manufacturer. Of the 24 Georgia asphalts, the manufacturers of 18 were known. Six were from Amoco Oil, Savannah, GA; six were from Shell Oil, Wood River, IL; five were from Chevron, Pascagoula, MS; and one was from Hunt Oil, Tuscaloosa, AL (see table 1). The procedure used was to compare statistically the various characterization parameter data (appendix A, tables 31-34), conducted using methods discussed in the experimental section, for all possible pairs of asphalts within any one manufacturer category and for each asphalt of an unknown manufacturer with each asphalt of a known manufacturer. Tables 8 and 9 list the acceptable ranges for the various characterization parameters. The test virgin asphalt pairs were considered to be the same asphalt if 8 of 10 parameters in tables 8 and 9 for each asphalt pair lay within the acceptable range. There is a certain amount of arbitrariness in categorizing pairs, as each member of a pair was probably processed on different days using slightly different processing conditions with slight variations within the crude state. Furthermore, storage, handling, and transportation operations for each member of a pair would probably be different.

Using the above procedure, 17 asphalt pairs were identified (table 10). Three pairs had both asphalts processed in a drum dryer mixer. Six pairs had both members processed in a batch (pug mill) mixer. Most importantly, eight pairs had one member processed in a batch mixer and the other member processed

Table 8. Asphalt standard deviation (SD) and acceptable ranges of asphalt property differences for physical, thermal and molecular size analytical methods.

	SD	Acceptable Range	
Pen 60 °F	0.35 dmm[1]		1 dmm[1]
Pen 77 °F	2.0 dmm[1]		3 dmm[1]
Vis 140 °F			100 poise[2]
Vis 275 °F			6 cst[3]
VTS		0.033[4]	
PVN_{140}		0.11[4]	
P1/P2	0.05[5]	0.2[5]	
Tpk2	1.19 °C[5]		4.0 °C[5]
LMS	0.714%[5]		2.5%[5]
SMS	0.740%[5]		2.6%[5]

[1] Standard deviations (SD) and ranges obtained from ASTM.(22)

[2] This repeatability figure, based on 7 percent of the mean of the virgin asphalts, was used directly as the acceptable range.(23)

[3] This repeatability figure, based on 1.8 percent of the mean of the virgin asphalts, was used directly as the acceptable range.(24)

[4] Value obtained from (Anderson, D., *unpublished data)*.

[5] The standard deviations and ranges were calculated using the procedures 1 and 2 in appendix E.

Table 9. Asphalt standard deviation (SD) and acceptable ranges of asphalt property differences for infrared analysis.

	SD[1]	Acceptable Range[1]
Infrared Area		
1	0.0072	0.0222
2	0.0167	0.0513
3	0.0129	0.0397
4	0.0439	0.1353
5	0.0153	0.0470
6	0.0060	0.0185
7	0.0347	0.1069
8	0.0058	0.0180

[1] The standard deviations (SD) and acceptable ranges were calculated using the procedures 1 and 2 in appendix E.

Table 10. FHWA # of Georgia's pairs.

DRUM vs BATCH		BATCH vs BATCH		DRUM vs DRUM	
8674	8688	8680	8684	8666	8672
8670	8680	8660	8662	8674	8690
8670	8684	8660	8684	8664	8678
8690	8688	8662	8680		
8690	8696	8688	8704		
8690	8704	8696	8704		
8674	8704				
8674	8696				

in a drum dryer. As further confirmation of the validity of these latter pairs, comparisons of the IR data showed that all drum - batch pairs had all eight infrared areas lying within the acceptable range. It should be noted that in assigning these pairs no asphalts of an unknown manufacturer matched against asphalts from more than one manufacturer. Also, in several cases one batch processed asphalt was matched against more than one drum dryer processed asphalt and vise-versa.

Having assigned the identical asphalt pairs by characterizing the virgin asphalts, recovered asphalt residues from each drum - batch pair were then characterized and compared. The results of Student's paired t-tests are given in table 11.(21) It can be seen that only 5 out of 17 parameters, the penetration, the viscosity at 140 °F (60 °C), the HP-GPC large molecular size (LMS), and two infrared areas, are statistically different.

These five parameters (table 11) provide a consistent view of the statistically significant differences. They show that the asphalts extracted from drum dryer mixes are harder with a lower penetration and greater viscosity at 140 °F (60 °C), have more agglomerated particles with a larger LMS content, and possibly are more oxidized with a higher carbonyl and oxidized nitrogen content than asphalts extracted from batch (pug mill) mixes.

C. Penetration Comparisons of TFO Residues with Drum Dryer Residues.

Penetrations of 55 virgin asphalts, recovered asphalts from drum dryer mixes using these virgin asphalts, and asphalt residues from TFO conditioning of these virgin asphalts are given in table 12. This table shows that the average penetration of the recovered asphalts is lower than that of the TFO residues, or that drum dryer operations harden asphalts more than TFO conditioning does.

A paper by Olsen and Granley discusses test results of penetrations of asphalt residues from drum dryer operations.(22) These tests were conducted in 1972 when drum dryers were first introduced as a means of producing asphaltic concrete for paving purposes. The authors compared penetrations of virgin asphalts, asphalts submitted to TFO conditioning, and recovered asphalts from laboratory simulated batch (pug mill) asphalt-aggregate mixing procedures with those of recovered asphalts from drum-dryer operations. They found that the

Table 11. Student's paired t-test(21) and selected means for various parameters for Georgia asphalt residues recovered from drum dryer vs. corresponding parameter for batch (pug mill) residues.

Parameter	Student's t	Mean	
		Drum	Batch
Pen 77 °F	-3.379*	26.62 dmm	31.00 dmm
Vis 140 °F	2.832*	19556 poise	11900 poise
Vis 275 °F	0.989 NS		
VTS	-1.388 NS		
PVN$_{140}$	2.213 NS		
P1/P2	-0.424 NS		
Tpk2	-0.685 NS		
LMS	2.844*	27.46%	24.25%
SMS	-1.701 NS		
A1	-1.165 NS		
A2	4.981**	0.410	0.358
A3	1.188 NS		
A4	-1.900 NS		
A5	1.116 NS		
A6	1.593 NS		
A7	-2.230 NS		
A8	4.498**	0.024	0.021

NS = Not Significant.

* = Significant at 95% probability level.

** = Significant at 99% probability level.

Table 12. Penetration at 77 °F (25 °C)[*] of the 55 virgin asphalts, recovered asphalts, and thin film oven residues.

FHWA #	VIR	REC	TFO
8509		38	135
8513	169	112	92
8515	108	58	59
8517	93	38	56
8519	142	70	86
8521	96	34	53
8523	73	24	44
8525	67	38	41
8527	108	38	64
8533	73	32	45
8535	73	45	45
8537	109	53	65
8543	104	41	63
8561	175	28	99
8564	113	36	62
8566	110	78	60
8570	98	51	66
8572	97	61	55
8576	102	32	56
8588	114	52	61
8590	66	58	43
8592	72	26	48
8596	145	44	77
8600	90	35	56
8612	134	45	75
8613	130	44	77
8615	117	53	64
8619	116	40	65
8621	128	55	71
8626	125	66	67
8628	90	35	55
8633	87	39	60
8637	91	43	59
8640	79	38	48
8642	63	31	38
8644	72	28	44
8650	88	57	51
8652	86	22	50
8656	81	21	43
8726	75	25	42
8732	69	25	42
8734	80	22	49
8736	241	33	119
8742	122	45	71
8744	117	36	69
8746	95	50	64
8748	90	41	64
8816	51	24	34
8820	42	13	31
8827	47	25	32
8831	53	13	35
8833	50	101	37
8839	100	32	61
8843	153	51	107
8845	136	49	82

	VIR	REC	TFO
Average	100.1	42.3	60.7
Std. Dev.	35.5	18.5	20.7

[*] All penetration values in dmm.

penetrations of 45 asphalts recovered from drum dryer operations were much higher than those of the corresponding virgin asphalts submitted to TFO conditioning tests. From this study by Granley and Olsen, "All penetration tests on recovered asphalt were well above the counterpart thin film oven test value(s) and also above those for simulated batch (pug mill) mixing tests on the original asphalt." Thus, the drum dryer operation was not hardening asphalts as much as the TFO conditioning or simulated batch mixing procedures were. FHWA endorsement of drum-dryer mixing procedures for producing asphaltic concretes was greatly influenced by these results.

The 1972 penetration results directly contradict our present penetration results of recovered asphalts from drum dryer operations versus TFO conditioned asphalts. When drum dryer mixers were introduced, the mix temperatures were very low (250 °F (122 °C)), and moisture contents in the finished mix were usually very high (above 1 percent in many cases). Apparently water aided the compaction process such that the compaction could be achieved below 250 °F (122 °C). These lower mix temperatures and higher moisture contents resulted in less premature hardening in drum mixes.(22)

However, stripping problems occurred with these mixes. As a result, States started to increase the mix temperatures and reduce the moisture contents in the finished mix. Thus, increased aging of asphalts has occurred.

CONCLUSIONS

1. Steam distillation of asphalts is not occurring in drum dryer operations.

2. The RFAD, TFO, and RTFO conditioned asphalts appear to have most properties closer to those of the recovered asphalt than those of the asphalts from steam distillation.

3. The recovered asphalts from drum dryer mixes, while only subtly different from those from batch (pug mill) mixes, were harder (lower penetration at 77 °F (25 °C) and higher viscosity at 140 °F (60 °C)), contained more agglomerated material content (higher LMS content), and were more oxidized (higher C=O and N-O content) than those recovered from batch (pug mill) mixes.

4. Asphalts recovered from recent drum-dryer operations are harder than those recovered from drum-dryer operations occurring 15 years ago.

Appendix A

Raw Data

The following tables show the raw data collected during this study and used in the statistical interpretation of the results.

Most conditioning or Abson recovery experiments were run once to afford one asphalt sample. The conditioning experiments, FAD, RFAD, and SSD, were run twice, affording two asphalt samples. The infrared and molecular size data were obtained using the residue from the first run of these conditioning experiments.

Penetration data were obtained using one sample of asphalt from each conditioning or recovery experiment following ASTM procedures.(15)

The data from viscosities at 140 and 275 °F were obtained with one determination for one asphalt from each conditioning or recovery procedure following ASTM procedures.(15)

The viscosity temperature susceptibility data were calculated by using the data from tables 14 (vis 140 °F (60 °C)) and 15 (vis 275 °F (135 °C)) and the following equation:(19)

$$\mathrm{VTS} = \frac{\log \log(100\ n_1) - \log \log(100 n_2)}{\log T_2 - \log T_1}$$

where: n_1 = viscosity at T_1, poises

n_2 = viscosity at T_2, poises

T = temperature, °Kelvin

The Penetration viscosity number (PVN_{140}) data were obtained by using the data from tables 13 (pen 77 °F (25 °C)) and 14 (vis 140 °F(60 °C)) and the following equation:(20)

$$\mathrm{PVN} = \left| \frac{6.489 - 1.590 \log P - \log X}{1.050 - 0.2234 \log P} \right| (-1.5)$$

where P = penetration at 77 °F (25 °C), dmm

X = viscosity at 140 °F (60 °C), poise

The thermal analysis data (P1/P2, and Tpk2) were obtained from one determination of one asphalt from each conditioning or recovery procedure.

The data for the large, medium, and small molecular size contents of asphalts were obtained as an average of two determinations on one asphalt from each conditioning or recovery procedure.

The eight infrared areas were obtained from one spectrum of one residue from each conditioning or recovery procedure.

Table 13. Penetration at 77 °F (dmm) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8509		38	135				101	122	176	
8513	169	112	92	73	159	131			134	125
8515	108	58	59	51	43	55	63	51	91	91
8517	93	38	56	45	35	40	43	44	86	80
8519	142	70	86	75	44	49			119	118
8521	96	34	53				42	42	78	
8523	73	24	44	28	82	79			57	56
8525	67	38	41	36	67	75	35	35	57	58
8527	108	38	64				57	54	90	
8533	73	32	45	34	43	57			61	63
8535	73	45	45	31	87	94			52	53
8537	109	53	65	46	49	53			79	82
8543	104	41	63	48	95	84			88	86
8561	175	28	99				65	70	137	
8564	113	36	62	55	44	34	55	58	94	95
8566	110	78	60	47	34	27			83	82
8570	98	51	66	51	99	112	56	55	90	88
8572	97	61	55	39	62	42			82	81
8576	102	32	56				45	55	76	
8588	114	52	61	46	118	104			81	90
8590	66	58	43	37	16	24	29	29	54	55
8592	72	26	48					42	62	
8596	145	44	77				62	56	109	
8600	90	35	56	47	106	69	47	46	82	83
8612	134	45	75				60	62	101	
8613	130	44	77				67	59	105	
8615	117	53	64	59	77	69	57	60	121	112
8619	116	40	65				67	64	99	
8621	128	55	71	50	144	109	64	63	116	113
8626	125	66	67	56	156	76	57	59	103	103
8628	90	35	55				42	44	73	
8633	87	39	60				44	49	76	
8637	91	43	59	48	36	35	52	51	81	81

Table 13. Penetration at 77 °F (dmm) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8640	79	38	48	36	57	61	40	38	66	67
8642	63	31	38				33	33	50	
8644	72	28	44				31	32	57	
8650	88	57	51	39	64	152	50	49	71	76
8652	86	22	50				44	44	62	
8656	81	21	43				47	43	61	
8726	75	25	42				36	36	50	
8732	69	25	42				37	44	55	
8734	80	22	49				44	43	61	
8736	241	33	119				104	98	194	
8742	122	45	71				57	53	98	
8744	117	36	69				60	55	86	
8746	95	50	64	56	38	31	55	53	82	84
8748	90	41	64				50	53	80	
8816	51	24	34	31	53	46	31	31	45	46
8820	42	13	31				26	25	36	
8827	47	25	32	23	92	26	19	26	46	40
8831	53	13	35				28	34	43	
8833	50	101	37				29	31	43	
8839	100	32	61				46	49	78	
8843	153	51	107	78	211	227	88	89	167	181
8845	136	49	82				69	68	108	

Table 14. Viscosity at 140 °F (poise) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8509	312	8861	762				1069	801	437	
8513	550	1056	1316	1728	585	753			768	848
8515	1263	3014	2958	3241	5734	3902		3724	1607	
8517	1187	7554	3562	4627	13578	9826	6949	6089	1712	
8519	717	3936	1939	2175	19804	6069			980	
8521	1352	5524	3823				6875	6278	1443	
8523	2313	46902	7627	17476	1807	1776			3610	3530
8525	2291	10512	7005	8651	2356	2172	2753	11201	2730	
8527	1079	5841	2494				2769	3041	1238	
8533	3003	15448	6618	10392	8753	6069			3559	2706
8535	2248	9727	8631	12712	1737	2092			4421	4170
8537	1095	3258	2469	3421	6250	4277			1984	1550
8543	1031	9976	3244	4746	2487	2522			1634	
8561	551	9831	1232				2223	2062	617	
8564	919	11442	3434	3466	8185	17823	4494	3924	1119	
8566	917	2639	4453	4786	1572	51632			2071	1619
8570	1557	9824	3762	4815	1406	1283	2836	2941	1707	
8572	1099	3355	2498	5445	2974	7327			1484	1482
8576	1073	11355	3244				5902	3642	1490	
8588	1073	4610	3386	4475	1091	1287			1642	
8590	2068	3644	6281	9668	205372	35859	14953	15151	3482	
8592	3360	23923	4825				2321	6803	2517	
8596	483	2714	1054					2137	574	
8600	1571	6563	3458	3978	1176	2416	4400	4501	2185	
8612	692	2956	1775				2579	2378	942	
8613	545	3772	1236				1713	2042	629	
8615	501	1968	1299	1593	1291	1714	2174		815	
8619	699	3131	1539				1553	1855	815	
8621	976	2067	1525	1993	770	862	1580	1850	832	
8626	831	2382	2235	2638	825	729	2766	2752	1331	
8628	1398	5940	3348				6914	4501	1661	
8633	1732	6035	3985				9298	8716	2048	
8637	1784	13249	4917	7191	1843	4432	7064	8410	2840	

Table 14. Viscosity at 140 °F (poise) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8640	2175	7459	5805	7598	3615	3622		8631	3348	
8642	2041	17280	5345				7824	7828	2380	
8644	2377	15313	8380				18438	21074	2748	
8650	1145	2841	2873	3529	2074	586	3661	3185	1675	
8652	1175	9664	2914				4384		1716	
8656	1284	11058	3637				4215	4423	1766	
8726	2171	37681	6459				10598		4269	
8732	2172	18088	6964				6715	9714	2873	
8734	2459	21269	5847				8173	8794	3422	
8736	295	13334	645				899	1057	338	
8742	513	2487	1406				1890	2641	627	
8744	838	5732	2029				2460	2635	1155	
8746	1644	12576	4530	4835	32036	60908	4984	8138	2437	
8748	1779	25322	3822				10430	6612	2162	
8816	1993	7760	3715	4118	2482	3137	4281	3685	2800	
8820	2330	15459	3897				4915	5204	2824	
8827	2465	7252	3916	4899	4391	6169	5736	5194	2924	
8831	1849	17054	3096				4435	3871	2160	
8833	2065	1083	3166				4217	4250	2366	
8839	965	8153	2145				3689	4000	1167	
8843	418	2571	792	863	372	375	602	681	580	
8845	779	3519	1634				2180	2216	979	

Table 15. Viscosity at 275 °F (poise) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD	SSD1	SSD2
8509	154	649	225					206	
8513	211	286	299	342	151	219		242	259
8515	303	466	468	466	740	477	486	366	
8517	307	612	475	499	733	679	567	355	
8519	264	535	373	382	826	708		295	
8521	307	690	535					359	
8523	408	1032	716	748	344	330		462	472
8525	420	792	658	697	392	360	462	449	
8527	297	696	423					329	
8533	420	843	652	694	594	523		555	428
8535	413	749	661	722	371	344		536	517
8537	299	523	424	470	539	501		375	345
8543	290	625	425	447	289	305		347	
8561	221	726	302					241	
8564	252	609	395	394	647	760	404	257	
8566	243	369	385	432	793	790		324	298
8570	377	711	502	577	323	347	614	386	
8572	298	476	467	506	411	553		336	332
8576	306	737	459					543	
8588	352	612	482	514	309	313		359	
8590	389	525	598	668	6162	1108	765	490	
8592	470	1087	609					546	
8596	196	375	313					217	
8600	341	658	508	514	309	402	554	410	
8612	242	507	358					281	
8613		454	288					242	
8615	194	313	350	277	277	302	305	231	
8619	199	395	291					256	
8621	194	328	281	309	314	219	288	221	
8626	258	453	398	416	229	202	408	360	
8628	337	632	485					377	
8633	460	1022	531					425	
8637	466	781	568	622	346	1097	634	472	

Table 15. Viscosity at 275 °F (poise) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD	SSD1	SSD2
8640	422	703	633	672	272	420	669	514	
8642	484	1087	586					547	
8644	410	1021	759					493	
8650	255	400	440	416	363	181	413	305	
8652	244	711	396					315	
8656	261	691	425					306	
8726	440	1378	790					596	
8732	410	1039	655					533	
8734	441	1003	659					536	
8736	157	400	248					179	
8742	202	365	315					222	
8744	255	558	376					333	
8746	393	861	618	551	1240	1506	561	501	
8748	398	1025	571					468	
8816	250	495	344	350	283	1080	381	293	
8820	290	595	381					294	
8827	310	627	402	466	162	516	473	353	
8831	227	622	281					245	
8833	253	202	315					305	
8839	289	667	391					315	
8843	182	375	263	240	190	145	244	209	
8845	250	480	349					284	

Table 16. Viscosity temperature susceptibility (poise/ °C) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	SSD1	SSD2
8509	-3.610	-3.737	-3.655					-3.487	
8513	-3.570	-3.580	-3.634	-3.630	-3.919	-3.675		-3.592	-3.574
8515	-3.605	-3.595	-3.584	-3.623	-3.479	-3.676		-3.543	
8517	-3.567	-3.725	-3.644	-3.704	-3.796	-3.740	-3.754	-3.595	
8519	-3.483	-3.587	-3.603	-3.630	-3.836	-3.533		-3.521	
8521	-3.622	-3.518	-3.576					-3.515	
8523	-3.599	-3.958	-3.608	-3.868	-3.643	-3.672		-3.672	-3.646
8525	-3.572	-3.648	-3.642	-3.674	-3.640	-3.679	-3.566	-3.586	
8527	-3.556	-3.532	-3.600					-3.525	
8533	-3.678	-3.736	-3.628	-3.743	-3.801	-3.768		-3.520	-3.622
8535	-3.578	-3.662	-3.714	-3.784	-3.563	-3.703		-3.630	-3.637
8537	-3.556	-3.533	-3.594	-3.637	-3.755	-3.671		-3.608	-3.578
8543	-3.558	-3.809	-3.699	-3.803	-3.922	-3.881		-3.595	
8561	-3.528	-3.689	-3.597					-3.499	
8564	-3.633	-3.877	-3.781	-3.787	-3.711	-3.862	-3.865	-3.700	
8566	-3.665	-3.736	-3.902	-3.834	-2.922	-4.184		-3.750	-3.722
8570	-3.505	-3.705	-3.621	-3.604	-3.594	-3.495	-3.353	-3.523	
8572	-3.561	-3.619	-3.519	-3.754	-3.692	-3.793		-3.583	-3.592
8576	-3.528	-3.729	-3.636					-3.190	
8588	-3.407	-3.542	-3.613	-3.668	-3.526	-3.585		-3.568	
8590	-3.594	-3.573	-3.675	-3.746	-3.273	-3.821	-3.797	-3.610	
8592	-3.630	-3.701	-3.563					-3.397	
8596	-3.580	-3.733	-3.500					-3.563	
8600	-3.594	-3.618	-3.579	-3.623	-3.558	-3.629	-3.602	-3.573	
8612	-3.546	-3.519	-3.602					-3.547	
8613		-3.703	-3.640					-3.504	
8615	-3.606	-3.759	-3.493	-3.780	-3.693	-3.734	-3.822	-3.660	
8619	-3.731	-3.745	-3.722					-3.567	
8621	-3.901	-3.738	-3.749	-3.775	-3.362	-3.734	-3.742	-3.710	
8626	-3.569	-3.525	-3.606	-3.635	-3.674	-3.736	-3.670	-3.479	
8628	-3.555	-3.612	-3.603					-3.532	
8633	-3.384	-3.260	-3.598					-3.517	
8637	-3.386	-3.740	-3.624	-3.694	-3.646	-3.094	-3.673	-3.561	

Table 16. Viscosity temperature susceptibility (poise/ °C) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	SSD1	SSD2
8640	-3.547	-3.614	-3.602	-3.655	-4.122	-3.751		-3.557	
8642	-3.410	-3.591	-3.631					-3.374	
8644	-3.606	-3.594	-3.598					-3.513	
8650	-3.716	-3.697	-3.623	-3.749	-3.653	-3.743	-3.769	-3.716	
8652	-3.767	-3.699	-3.715					-3.698	
8656	-3.744	-3.768	-3.743					-3.735	
8726	-3.512	-3.685	-3.474					-3.533	
8732	-3.570	-3.638	-3.643					-3.469	
8734	-3.560	-3.719	-3.574					-3.532	
8736	-3.564	-4.268	-3.493					-3.501	
8742	-3.579	-3.721	-3.616					-3.581	
8744	-3.583	-3.696	-3.615					-3.486	
8746	-3.493	-3.649	-3.528	-3.642	-3.705	-3.778	-3.639	-3.453	
8748	-3.514	-3.762	-3.525					-3.460	
8816	-3.963	-3.902	-3.928	-3.953	-3.940	-2.973	-3.896	-3.957	
8820	-3.893	-4.000	-3.860					-3.957	
8827	-3.858	-3.691	-3.817	-3.781	-4.679	-3.785	-3.828	-3.813	
8831	-4.020	-4.000	-4.033					-4.013	
8833	-3.966	-3.907	-3.942					-3.855	
8839	-3.532	-3.686	-3.605					-3.538	
8843	-3.584	-3.712	-3.530	-3.650	-3.489	-3.756	-3.477	-3.603	
8845	-3.569	-3.631	-3.590					-3.554	

Table 17. Penetration viscosity number (PVN) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8509		-0.064	-0.574				-0.680	-0.689	-0.761	
8513	-0.560	-0.525	-0.607	-0.684	-0.596	-0.639			-0.578	-0.584
8515	-0.389	-0.471	-0.464	-0.591	-0.292	-0.296		-0.455	-0.412	
8517	-0.700	-0.213	-0.359	-0.430	0.210	0.110	-0.109	-0.201	-0.436	
8519	-0.557	0.094	-0.305	-0.405	0.924	-0.041			-0.506	
8521	-0.509	-0.660	-0.372				-0.154	-0.241	-0.768	
8523	-0.384	0.762	0.014	0.112	-0.456	-0.533			-0.318	-0.368
8525	-0.527	0.096	-0.172	-0.165	-0.498	-0.406	-1.264	0.033	-0.595	
8527	-0.561	-0.453	-0.511				-0.581	-0.569	-0.707	
8533	-0.115	0.196	-0.087	-0.079	0.110	0.196			-0.228	-0.453
8535	-0.413	0.281	0.167	-0.028	-0.402	-0.077			-0.259	-0.287
8537	-0.530	-0.529	-0.498	-0.688	-0.013	-0.262			-0.417	-0.616
8543	-0.672	0.162	-0.271	-0.310	0.126	-0.067			-0.448	
8561	-0.496	-0.403	-0.559				-0.604	-0.567	-0.789	
8564	-0.663	0.094	-0.239	-0.413	0.082	0.418	-0.157	-0.209	-0.746	
8566	-0.709	-0.141	-0.030	-0.333	-1.817	1.027			-0.293	-0.571
8570	-0.324	0.490	-0.048	-0.205	-0.417	-0.310	-0.584	-0.575	-0.366	
8572	-0.715	-0.287	-0.736	-0.482	-0.383	-0.094			-0.662	-0.682
8576	-0.660	-0.085	-0.451				-0.197	-0.364	-0.775	
8588	-0.477	-0.218	-0.278	-0.430	-0.401	-0.431			-0.575	
8590	-0.654	-0.283	-0.205	-0.022	1.418	0.526	0.023	0.035	-0.436	
8592	-0.022	0.285	-0.294					-0.164	-0.550	
8596	-0.975	-0.972	-1.114					-0.863	-1.237	
8600	-0.454	-0.461	-0.388	-0.512	-0.498	-0.427	-0.414	-0.424	-0.257	
8612	-0.696	-0.859	-0.614				-0.575	-0.607	-0.817	
8613	-1.016	-0.658	-0.949				-0.822	-0.833	-1.195	
8615	-1.277	-1.023	-1.168	-1.080	-0.903	-0.777	-0.821		-0.683	
8619	-0.922	-0.967	-0.975				-0.921	-0.809	-1.005	
8621	-0.386	-0.922	-0.854	-1.092	-0.451	-0.792	-0.971	-0.835	-0.730	
8626	-0.607	-0.510	-0.552	-0.655	-0.229	-1.514	-0.582	-0.536	-0.411	
8628	-0.578	-0.553	-0.447				-0.149	-0.489	-0.724	
8633	-0.405	-0.386	-0.141				0.203	0.309	-0.446	
8637	-0.301	0.504	0.042	0.091	-1.600	-0.824	0.199	0.338	-0.003	

Table 17. Penetration viscosity number (PVN) of
the virgin asphalts, recovered asphalts, and
laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8640	-0.322	-0.225	-0.116	-0.286	-0.317	-0.210		-0.088	-0.166	
8642	-0.737	0.251	-0.536				-0.382	-0.382	-0.920	
8644	-0.377	-0.006	0.104				0.310	0.479	-0.589	
8650	-0.825	-0.556	-0.708	-0.889	-0.697	-0.672	-0.501	-0.666	-0.758	
8652	-0.833	-0.739	-0.723				-0.514		-0.934	
8656	-0.832	-0.682	-0.725				-0.456	-0.539	-0.929	
8726	-0.406	0.630	-0.214				0.023		-0.352	
8732	-0.536	-0.018	-0.142				-0.361	0.245	-0.598	
8734	-0.174	-0.054	-0.077				0.080	0.115	-0.267	
8736	-0.671	0.106	-0.970				-0.821	-0.741	-0.898	
8742	-1.186	-1.024	-0.937				-0.959	-0.735	-1.303	
8744	-0.708	-0.547	-0.605				-0.622	-0.683	-0.851	
8746	-0.317	0.698	0.090	-0.057	1.137	1.396	-0.055	0.368	-0.143	
8748	-0.322	1.041	-0.081				0.516	0.165	-0.308	
8816	-1.065	-0.818	-1.026	-1.053	-0.796	-0.771	-1.017	-1.154	-0.911	
8820	-1.180	-0.990	-1.103				-1.119	-1.118	-1.204	
8827	-0.972	-0.825	-1.057	-1.275	0.677	-0.918	-1.368	-1.070	-0.838	
8831	-1.084	-0.910	-1.156				-1.117	-0.988	-1.220	
8833	-1.058	-0.666	-1.061				-1.117	-1.024	-1.134	
8839	-0.807	-0.388	-0.735				-0.615	-0.445	-0.989	
8843	-1.052	-0.816	-0.914	-1.302	-0.630	-0.484	-1.505	-1.358	-0.519	
8845	-0.537	-0.569	-0.561				-0.532	-0.538	-0.667	

Table 18. Peak area ratios (P1/P2) of the thermograms of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8509	1.4									
8513	1.2	1.6	1.5	1.5	1.4	1.4			1.5	
8515	1.4	1.3	1.5	1.5	1.6	1.5	1.4	1.4	1.4	1.5
8517	1.4	0.9	1.5	1.6	1.6	1.6	1.3	1.2	1.5	
8519	1.1	1.3	1.7	1.2	1.3	1.9			1.2	1.5
8521										
8523	1.3	1.1	1.3	1.5	1.5	1.4			1.5	0.6
8525	1.4	1.0	1.7	1.8	1.2	1.5	1.4	1.2	1.5	1.6
8527	1.5									
8533	1.6	0.6	1.8	1.6	1.6	1.7			1.5	1.4
8535	1.7	0.8	1.5	1.6	1.5	1.4			1.6	1.4
8537	1.3	1.5	1.4	1.4	1.5	1.3			1.7	1.7
8543	1.1	1.2	1.6	1.3	0.9	1.3			1.2	1.2
8561	1.4									
8564	1.3	1.5	1.5	1.2	1.4	1.5	1.5	1.3	1.6	1.4
8566	1.2	1.1	1.3	1.5	1.3	1.1			1.3	
8570	1.5	1.5	1.5	1.2	1.4	1.3	1.4	1.4	1.4	1.5
8572	1.5	1.4	1.6	1.4	1.7	1.0			1.6	
8576										
8588	1.3	1.3	1.7	1.5	1.3	1.4			1.7	1.7
8590	1.4	1.5	1.5	1.6	1.7	1.7	1.2	1.5	1.6	1.5
8592										
8596										
8600	1.4	1.5	1.6	1.6	1.5	1.5	1.4	1.5	1.5	1.3
8612										1.3
8613										
8615	1.0	1.4	1.4	1.3	1.4	1.4	1.5	1.5	1.6	
8619										
8621	1.4	1.3	1.1	1.4	1.2	1.4	1.2	1.6	1.3	1.3
8626	1.3	1.5	1.6	1.5	1.4	1.4	1.5	1.5	1.5	1.5
8628										
8633										
8637	1.5	1.6	1.7	1.4	1.4	1.5	1.3	1.4	1.4	1.4

Table 18. Peak area ratios (P1/P2) of the thermograms of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8640	1.4	1.5	1.6	1.5	1.4	1.4	1.7	1.9	1.4	
8642										
8644										
8650	1.3	1.7	1.5	1.7	1.5	1.2	1.7	1.7	1.6	
8652										
8656										
8726										
8732										
8734										
8736										
8742										
8744										
8746	1.6	1.4	1.5	1.3	1.4	1.5	1.4	1.6	1.6	
8748										
8816	1.3	1.6	1.2		1.5	1.7	1.4	1.5	1.6	
8820										
8827	1.6	1.7	1.7	1.4	1.5	1.5	1.5	1.4	1.6	
8831										
8833										
8839										
8843	1.3	1.5		1.3	1.4	1.4	1.3	1.2	1.4	
8845										

Table 19. Maximum temperature at second peak in °C (Tpk2) of the thermograms of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8509	464									
8513	471	469	469	466	476	474			473	
8515	470	466	467	472	474	477	468	466	470	467
8517	462	462	462	462	462	459	457	456	469	
8519	463	473	472	466	473	476			471	465
8521										
8523	465	466	466	457	464	465			492	510
8525	463	490	463	462	461	460	457	457	464	464
8527	465									
8533	463	470	469	460	462	462			460	
8535	460	460	464	457	461	460			460	460
8537	468	473	474	466	477	470			476	
8543	470	473	474	468	478	476			470	469
8561	466									
8564	476	472	470	468	476	475	465	468	474	470
8566	468	461	473	473	471	478			468	
8570	468	468	467	470	470	470	464	468	470	466
8572	466	468	464	460	466	473			465	
8576										
8588	466	463	463	456	467	465			463	463
8590	464	460	463	455	466	469	456	460	461	460
8592										
8596										
8600	477	474	469	465	472	474	472	470	472	467
8612										468
8613										
8615	466	465	472	466	472	472	468	465	472	
8619										
8621	473	456	475	475	475	475	474	467	477	472
8626	473	463	470	472	473	470	470	471	471	469
8628										
8633										

Table 19. Maximum temperature at second peak in °C (Tpk2) of the thermograms of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD1	FAD2	RFAD1	RFAD2	SSD1	SSD2
8637	472	464	468	470	469	471	466	466	466	466
8640	474	465	475	466	474	475	474	475	470	
8642										
8644										
8650	465	461	465	467	469	465	460	464	462	
8652										
8656										
8726										
8732										
8734										
8736										
8742										
8744										
8746	467	465	470	465	465	467	468	465	465	
8748										
8816	466	460	468		474	470	464	463	462	
8820										
8827	468	470	470	470	470	470	468	470	468	
8831										
8833										
8839										
8843	473	464		475	472	469	472	470	469	
8845										

Table 20. Large molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	14.57	26.57	19.18			20.55	14.44
8513	26.17	31.01	28.95	28.95	18.86		26.25
8515	22.23	23.19	28.35	26.46	20.33	26.46	23.25
8517	20.69	29.33	28.16	27.34	24.03	28.98	21.61
8519	30.19	35.07	33.27	31.47	31.12		25.64
8521	16.69	20.23	19.95			21.81	15.98
8523	19.42	27.94	27.96	29.52	15.02		22.21
8525	19.16	28.86	24.83	24.97	18.21	19.86	21.13
8527	19.47	22.43	23.30			24.12	18.63
8533	25.38	32.86	28.10	30.20	18.59		25.27
8535	20.04	32.13	26.66	26.02	15.97		22.72
8537	23.66	29.25	26.67	28.10	24.29		22.29
8543	28.84	37.18	27.97	34.66	25.30		20.10
8561	19.37	27.85	22.38			25.19	18.12
8564	11.42	20.78	20.11	19.27	14.00	19.35	15.81
8566	15.38		23.96	24.52	18.58		16.03
8570	28.62	34.78	32.80	32.68	23.82	27.26	27.60
8572	19.48	28.35	25.49	25.66	16.61		19.23
8576	16.07	22.92	19.66			21.90	16.20
8588	18.10	25.41	22.75	23.84	17.37		18.02
8590	24.61	30.33	26.18	30.14	27.17	29.24	23.04
8592	25.55	33.84	27.87			32.32	26.10
8596	16.44	25.60	19.56			21.09	15.84
8600	32.33	36.93	34.58	34.93	27.30	35.65	31.77
8612	20.60	24.88	23.60			25.99	20.24
8613	16.87	21.13	19.71			20.93	15.70
8615	24.22	28.92	28.92	28.28	19.61	30.67	23.30
8619	10.53	15.53	14.34			14.95	10.04
8621	13.40	22.22	17.12	16.08	11.96	18.19	13.78
8626	22.78	30.41	27.30	28.88	19.21	30.00	23.44
8628	20.86	25.94	25.25			22.75	20.98
8633	28.10	34.83	33.09			34.20	26.46

Table 20. Large molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	31.93	41.96	33.23	38.12	34.04	39.25	31.65
8640	26.71	30.57	28.92	31.30	29.78	29.78	27.53
8642	17.35	29.31	21.03			22.20	16.86
8644	17.66	25.68	21.35			22.73	17.14
8650	24.70	30.87	30.01	30.30	24.23	31.71	26.43
8652	18.28	23.37	22.06			20.55	16.68
8656	17.79	22.08	23.16			22.95	18.17
8726	23.11	22.97	26.04			23.90	21.25
8732	20.25	25.66	23.64			25.05	19.13
8734	21.91	22.08	26.68			28.28	21.47
8736	16.79	28.94	21.03			21.80	16.49
8742	21.35	25.56	24.01			25.96	19.63
8744	18.99	21.87	22.24			22.90	18.83
8746	36.70	46.06	43.13	39.37	40.11	43.51	38.74
8748	31.73	36.04	34.95			34.37	29.82
8816	19.18	28.72	23.87		17.02	23.08	20.21
8820	6.13	10.94	15.86			9.80	5.49
8827	14.28	22.47	18.32	18.32	12.95	19.80	14.52
8831	5.23	14.23	8.30			13.68	5.37
8833	5.46	23.38	7.35			13.71	5.95
8839	15.24	23.32	19.67			21.97	14.98
8843	13.26	25.78		17.37	12.65	13.98	13.14
8845	18.63	24.54				23.51	18.47

Table 21. Medium molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	44.47	44.38	42.78			42.01	44.51
8513	43.34	41.57	41.65	41.82	45.78		44.09
8515	45.84	45.53	42.98	43.56	47.03	43.56	45.46
8517	46.68	42.41	43.57	43.00	45.32	43.05	46.48
8519	46.29	45.32	45.81	46.88	47.96		50.50
8521	49.76	48.07	47.95			47.15	49.79
8523	47.68	45.24	44.65	42.90	49.44		47.69
8525	47.90	42.99	45.44	44.96	47.50	47.26	46.99
8527	49.10	47.28	47.17			37.93	49.18
8533	43.74	40.02	42.10	40.91	44.42		43.91
8535	44.16	41.16	43.90	43.50	47.58		45.31
8537	46.92	43.58	45.38	44.37	46.75		47.54
8543	43.65	40.51	44.83	40.97	46.30		46.56
8561	48.66	45.41	46.49			45.24	48.15
8564	49.52	47.83	48.43	47.85	54.56	48.16	49.03
8566	51.02		46.29	45.94	49.87		50.58
8570	47.78	44.44	45.32	46.16	48.72	48.16	48.86
8572	45.73	43.13	43.74	43.29	46.09		45.81
8576	50.16	47.76	48.36			47.46	49.59
8588	47.55	45.49	46.22	45.25	47.46		47.90
8590	44.39	41.38	42.74	41.19	43.58	41.69	45.04
8592	52.42	47.02	50.81			48.02	52.03
8596	50.56	45.46	49.13			48.17	50.57
8600	40.58	38.90	39.89	39.23	43.07	39.12	40.98
8612	45.95	44.34	44.52			42.96	46.21
8613	51.83	49.75	50.19			49.63	51.81
8615	44.11	42.30	40.99	42.06	46.57	41.30	44.72
8619	46.27	45.86	45.23			45.13	46.01
8621	42.65	40.85	42.22	42.55	43.09	41.69	42.00
8626	43.01	40.07	40.52	39.91	43.52	39.45	40.75
8628	48.04	45.80	46.06			46.25	48.25
8633	49.84	45.67	46.38			45.58	50.44

Table 21. Medium molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	47.45	40.96	46.73	42.22	45.09	41.97	47.11
8640	40.48	38.48	40.33	38.37	39.54		41.16
8642	53.89	44.64	51.73			51.35	53.93
8644	46.61	45.64	44.93			44.23	46.24
8650	43.23	41.26	40.71	41.53	44.79	39.70	41.84
8652	48.57	46.89	46.58			47.08	48.92
8656	49.17	47.70	46.28			46.18	48.67
8726	47.55	44.39	46.03			45.83	47.62
8732	48.24	45.27	46.46			45.62	48.75
8734	48.47	51.10	45.86			44.68	48.52
8736	47.91	43.99	45.73			45.10	47.52
8742	46.69	44.81	45.19			44.15	47.24
8744	48.05	46.55	46.36			45.72	47.63
8746	43.21	38.46	39.18	41.27	40.65	39.61	42.59
8748	47.94	45.86	45.55			45.14	48.76
8816	46.71	43.44	45.24		47.89	45.20	47.83
8820	49.72	50.04	50.29			49.27	49.28
8827	50.30	46.51	48.42	48.26	48.80	48.56	49.79
8831	48.15	48.70	48.64			47.88	48.51
8833	49.06	42.88	49.90			48.09	49.20
8839	51.06	48.19	49.23			48.19	51.48
8843	49.72	45.71		48.27	48.98	49.57	49.52
8845	48.39	45.90				45.84	48.34

Table 22. Small molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	40.96	28.05	38.04			37.44	41.06
8513	30.50	27.43	29.63	28.87	35.37		29.67
8515	31.94	31.29	28.68	29.99	32.64	29.99	31.29
8517	32.64	28.27	28.28	29.48	30.65	27.98	31.91
8519	23.52	19.61	20.93	21.66	20.92		23.86
8521	33.55	31.71	32.09			31.04	34.23
8523	32.91	26.82	27.39	27.59	35.55		30.10
8525	32.95	28.17	29.74	30.08	34.29	32.89	31.90
8527	31.42	30.30	29.53			29.43	32.19
8533	30.88	27.12	29.73	28.89	37.00		30.83
8535	35.81	26.72	29.45	30.49	36.45		31.98
8537	29.44	27.17	27.96	27.53	28.97		30.20
8543	27.52	22.32	27.21	24.38	28.42		33.35
8561	31.97	26.74	31.13			29.57	33.73
8564	39.07	31.39	31.46	32.73	31.45	32.50	35.17
8566	33.60		29.75	44.54	31.55		33.39
8570	23.61	20.79	21.89	21.16	27.46	24.59	23.55
8572	34.79	28.53	30.78	31.05	37.31		34.96
8576	33.78	29.31	31.98			30.85	34.21
8588	34.36	29.11	31.03	30.92	35.18		34.09
8590	31.01	28.30	31.09	28.68	29.26	29.07	31.92
8592	22.02	19.15	21.32			19.66	21.87
8596	33.00	28.94	31.30			30.74	33.59
8600	27.10	24.18	25.55	25.86	29.63	25.24	27.25
8612	33.45	30.78	31.88			31.05	33.55
8613	31.29	29.12	30.10			29.44	32.49
8615	31.68	28.79	30.10	29.67	33.82	28.03	31.99
8619	43.16	38.61	40.42			39.93	43.95
8621	43.96	36.93	41.17	41.37	44.96	40.12	44.22
8626	34.32	29.53	32.19	31.21	37.28	30.56	35.81
8628	31.10	28.26	28.69			31.01	30.77
8633	22.07	19.50	20.53			20.22	23.10

Table 22. Small molecular size contents of the gel permeation chromatographs of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	20.63	17.09	20.05	19.67	20.87	18.78	21.24
8640	32.82	30.96	30.76	30.34	30.69		31.31
8642	28.76	26.04	27.24			26.45	29.21
8644	35.73	28.68	33.72			33.04	36.62
8650	32.08	27.87	29.29	28.17	30.99	28.59	31.74
8652	33.14	29.74	31.35			32.37	34.41
8656	33.04	30.22	30.55			30.87	33.16
8726	29.34	32.64	27.93			30.27	31.13
8732	31.51	29.07	29.89			29.32	32.12
8734	29.61	26.82	27.40			27.04	30.01
8736	35.30	27.07	33.24			33.10	35.99
8742	31.96	29.63	30.80			29.90	33.13
8744	32.97	31.58	31.40			31.38	33.54
8746	20.09	15.49	17.71	19.36	19.25	16.88	18.68
8748	20.33	18.10	19.49			20.49	21.42
8816	34.12	27.84	30.90		35.10	31.73	31.97
8820	44.15	39.01	33.85			40.93	45.23
8827	35.43	31.02	33.26	33.42	38.26	31.65	35.70
8831	46.63	37.07	43.06			38.44	46.12
8833	45.48	33.75	42.75			38.20	44.85
8839	33.70	28.50	31.10			29.83	33.54
8843	37.02	28.52		34.37	38.37	36.45	37.34
8845	32.98	29.56				30.65	33.18

Table 23. Infrared area ratios in the regions 1775 -1670 cm^{-1} (A1) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	-0.043	0.081	0.020			-0.026	-0.031
8513	-0.010	0.030	0.037	-0.015	0.032		-0.005
8515	-0.019	0.020	0.002	-0.003	0.049	-0.015	-0.011
8517	-0.044	0.018	-0.049	-0.035	0.012	-0.046	-0.041
8519	0.016	0.066	0.050	-0.009	0.053		-0.003
8521	-0.055	0.031	-0.007			-0.041	-0.049
8523	0.013	0.123	0.055	0.020	-0.010		0.014
8525	-0.048	0.045	-0.070	-0.057	-0.042	-0.054	-0.076
8527	-0.047	0.020	0.026			-0.038	-0.031
8533	-0.048	0.035	0.004	-0.039	-0.034		-0.029
8535	-0.060	0.023	-0.044	-0.048	-0.074		-0.048
8537	-0.036	0.065	-0.016	-0.019	0.012		-0.027
8543	0.033	0.101	0.011	0.036	0.017		0.033
8561	-0.056	0.077	-0.006			-0.025	-0.053
8564	-0.049	0.066	0.023	-0.045	-0.023	-0.049	-0.060
8566	-0.041	0.077	-0.046	-0.027	-0.010		-0.042
8570	-0.010	0.039	-0.011	-0.011	-0.022	-0.019	-0.006
8572	-0.032	0.006	0.001	-0.031	-0.047		
8576	-0.029	0.020	0.016			-0.038	-0.052
8588	-0.040	0.039	-0.119	-0.044	-0.100		
8590	-0.038	0.016	-0.050	-0.046	-0.019	-0.056	-0.068
8592	0.006	0.114	0.025			-0.016	-0.067
8596	-0.067	0.047	-0.028			-0.018	-0.041
8600	-0.041	0.020	-0.016	-0.040	-0.050	-0.025	-0.024
8612	-0.032	0.050	-0.015			-0.010	-0.046
8613	-0.049	0.077	0.002			-0.026	-0.034
8615	-0.000	0.018	-0.010	-0.001	0.007	0.001	-0.039
8619	-0.024	0.043	0.005			-0.049	-0.041
8621	-0.040	0.034	0.002	-0.023	-0.035	-0.035	-0.051
8626	0.017		-0.060	-0.018	-0.106	0.009	-0.032
8628	-0.004	0.035	0.016			-0.032	0.009
8633	-0.030	0.081	0.076			-0.008	0.021

Table 23. Infrared area ratios in the regions 1775 -1670 cm^{-1} (A1) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.007	0.080	-0.027	0.008	0.013	-0.022	-0.037
8640	-0.001	0.027	-0.037	0.001	0.013	-0.021	-0.018
8642	-0.037	0.048	-0.001			-0.021	-0.027
8644	-0.066	0.032	-0.015			-0.056	-0.075
8650	-0.055	0.049	-0.059	-0.069	-0.071	-0.064	-0.083
8652	-0.076	0.024	0.012			-0.039	-0.051
8656	-0.076	0.024	-0.036			-0.074	-0.111
8726	-0.033	0.010	-0.008			-0.029	-0.059
8732	-0.026	-0.001	-0.025			-0.064	-0.059
8734	0.028	0.079	0.052			0.013	-0.012
8736	-0.029	0.085	0.018			-0.040	-0.035
8742	-0.017	0.021	0.000			-0.005	-0.036
8744	-0.033	0.039	-0.001				-0.060
8746	-0.042	0.043	-0.021	-0.012	0.028	-0.005	-0.032
8748	0.017	0.059	0.040			-0.007	-0.028
8816	-0.021	0.067	0.028		-0.024	0.012	-0.016
8820	0.029	0.111	0.052			-0.029	-0.061
8827	-0.011	0.093	-0.104	-0.005	-0.059	-0.086	-0.074
8831	-0.034	0.107	0.034			0.006	-0.038
8833	-0.007	0.267	0.012			-0.026	-0.058
8839	0.002	0.050	0.023			-0.015	-0.029
8843	0.002	0.083		-0.006	-0.018	-0.011	-0.036
8845	-0.033	0.043				-0.044	-0.064

Table 24. Infrared area ratios in the regions 1670 - 1532 cm^{-1} (A2) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.370	0.255	0.326			0.363	0.388
8513	0.353	0.331	0.379	0.379	0.386		0.341
8515	0.390	0.336	0.351	0.284	0.366	0.387	0.354
8517	0.389	0.310	0.371	0.386	0.377	0.411	0.344
8519	0.347	0.368	0.362	0.369	0.359		0.327
8521	0.387	0.278	0.436			0.387	0.401
8523	0.357	0.322	0.352	0.382	0.322		0.350
8525	0.390	0.335	0.378	0.406	0.393	0.354	0.437
8527	0.402	0.310	0.389			0.376	0.396
8533	0.376	0.342	0.361	0.381	0.417		0.327
8535	0.375	0.312	0.299	0.374	0.423		0.381
8537	0.369	0.311	0.385	0.367	0.387		0.356
8543	0.340	0.326	0.368	0.356	0.383		0.317
8561	0.402	0.256	0.373			0.379	0.393
8564	0.431	0.377	0.445	0.448	0.451	0.472	0.429
8566	0.413	0.389	0.449	0.415	0.417		0.401
8570	0.359	0.324	0.367	0.364	0.391	0.405	0.312
8572	0.351	0.350	0.383	0.359	0.430		
8576	0.346	0.286	0.316			0.375	0.396
8588	0.343	0.312	0.345	0.372	0.436		
8590	0.367	0.304	0.405	0.366	0.392	0.403	0.410
8592	0.377	0.324	0.448			0.440	0.410
8596	0.384	0.265	0.343			0.346	0.387
8600	0.398	0.326	0.326	0.457	0.393	0.394	0.378
8612	0.364	0.278	0.333			0.362	0.377
8613	0.359	0.310	0.346			0.373	0.355
8615	0.311	0.316	0.327	0.344	0.373	0.279	0.406
8619	0.354	0.294	0.362			0.411	0.360
8621	0.387	0.322	0.403	0.369	0.390	0.380	0.395
8626	0.292		0.278	0.432	0.514	0.295	0.426
8628	0.349	0.307	0.365			0.391	0.398
8633	-0.924	0.288	2.159			0.374	0.560

Table 24. Infrared area ratios in the regions 1670 - 1532 cm^{-1} (A2) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.354	0.320	0.332	0.390	0.384	0.411	0.425
8640	0.312	0.334	0.340	0.459	0.387	0.422	0.412
8642	0.386	0.322	0.405			0.414	0.420
8644	0.409	0.308	0.420			0.384	0.407
8650	0.447	0.404	0.521	0.631	0.549	0.560	0.554
8652	0.513	0.371	0.379			0.528	0.508
8656	0.507	0.363	0.444			0.548	0.529
8726	0.380	0.329	0.431			0.413	0.415
8732	0.346	0.332	0.393			0.422	0.461
8734	0.414	0.340	0.322			0.413	0.405
8736	0.358	0.296	0.326			0.333	0.404
8742	0.353	0.284	0.345			0.290	0.368
8744	0.358	0.291	0.303				0.403
8746	0.371	0.302	0.357	0.393	0.387	0.296	0.421
8748	0.333	0.258	0.338			0.352	0.375
8816	0.508	0.437	0.457		0.526	0.527	0.530
8820	0.406	0.386	0.438			0.479	0.356
8827	0.425	0.356	0.356	0.557	0.496	0.482	0.514
8831	0.475	0.340	0.406			0.474	0.455
8833	0.519	0.176	0.513			0.527	0.578
8839	0.338	0.298	0.356			0.384	0.394
8843	0.342	0.273		0.461	0.388	0.367	0.393
8845	0.376	0.275				0.402	0.398

Table 26. Infrared area ratios in the regions 1113 - 983 cm^{-1} (A4) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.081	0.285	0.132			0.168	0.062
8513	0.113	0.170	0.115	0.125	0.074		0.089
8515	0.033	0.173	0.162	0.106	0.113	0.061	0.042
8517	0.088	0.238	0.190	0.135	0.120	0.112	0.030
8519	0.083	0.049	0.104	0.090	0.102		0.057
8521	0.119	0.219	0.160			0.116	0.025
8523	0.077	0.154	0.115	0.091	0.080		0.081
8525	0.152	0.181	0.116	0.111	0.108	0.033	0.054
8527	0.111	0.212	0.261			0.146	0.093
8533	0.102	0.168	0.164	0.132	0.075		0.127
8535	0.084	0.222	0.199	0.124	0.022		0.083
8537	0.128	0.195	0.093	0.151	0.105		0.065
8543	0.097	0.123	0.107	0.090	0.106		0.047
8561	0.131	0.293	0.091			0.099	0.067
8564	0.077	0.174	0.097	0.083	0.068	0.075	0.028
8566	0.118	0.106	0.049	0.085	0.123		0.077
8570	0.097	0.171	0.043	0.086	0.063	0.076	0.012
8572	0.170	0.157	0.196	0.140	0.062		
8576	0.163	0.290	0.211			0.076	-0.033
8588	0.149	0.212	0.143	0.132	0.062		
8590	0.159	0.159	0.063	0.029	0.131	0.140	0.095
8592	0.099	0.145	0.184			0.035	0.038
8596	0.102	0.240	0.151			0.106	0.064
8600	0.039	0.165	0.174	0.089	0.082	0.099	0.152
8612	0.093	0.189	0.162			0.134	0.160
8613	0.081	0.204	0.169			0.119	0.009
8615	0.017	0.186	0.076	0.123	0.080	0.083	0.050
8619	0.199	0.261	0.142			0.123	0.032
8621	0.112	0.212	0.128	0.137	0.076	0.100	0.102
8626	0.149		0.200	0.198	-0.064	0.103	0.125
8628	0.145	0.209	0.289			0.153	0.077
8633	-0.147	0.242	-0.213			0.128	0.616

Table 26. Infrared area ratios in the regions 1113 - 983 cm^{-1} (A4) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.092	0.156	0.052	0.117	0.081	0.071	0.060
8640	0.080	0.191	0.100	0.210	0.068	0.092	0.048
8642	0.141	0.270	0.119			0.073	0.022
8644	0.082	0.187	0.250			0.108	0.102
8650	0.036	0.196	0.102	0.140	0.032	0.026	0.023
8652	0.123	0.299	0.220			0.051	-0.031
8656	0.060	0.321	0.138			0.076	0.104
8726	0.177	0.250	0.017			0.061	0.058
8732	0.155	0.300	0.110			0.096	-0.011
8734	0.024	0.078	0.108			0.068	0.083
8736	0.148	0.323	0.118			0.191	-0.007
8742	0.170	0.322	0.110			0.352	0.157
8744	0.126	0.290	0.206				0.125
8746	0.064	0.257	0.046	0.107	0.060	0.309	0.033
8748	0.014	0.373	0.111			0.081	0.073
8816	0.103	0.113	0.089		0.058	0.021	0.070
8820	0.147	0.171	0.227			0.045	0.097
8827	0.044	0.209	0.122	0.142	0.046	0.073	0.048
8831	0.052	0.291	0.155			0.015	0.053
8833	0.136	0.260	0.133			0.076	0.094
8839	0.098	0.267	0.117			0.114	0.126
8843	0.139	0.275		0.177	0.079	0.072	0.120
8845	0.144	0.273				0.101	-0.007

Table 27. Infrared area ratios in the regions 917 - 843 cm^{-1} (A5) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.066	0.091	0.119			0.108	0.116
8513	0.100	0.089	0.095	0.100	0.106		0.112
8515	0.112	0.088	0.096	0.107	0.100	0.113	0.113
8517	0.117	0.091	0.121	0.108	0.099	0.123	0.128
8519	0.137	0.125	0.122	0.132	0.127		0.155
8521	0.060	0.090	0.086			0.110	0.102
8523	0.138	0.106	0.117	0.127	0.169		0.144
8525	0.106	0.098	0.113	0.113	0.108	0.137	0.151
8527	0.126	0.086	0.075			0.105	0.128
8533	0.111	0.088	0.096	0.107	0.122		0.124
8535	0.119	0.090	0.095	0.106	0.125		0.116
8537	0.116	0.094	0.115	0.107	0.112		0.131
8543	0.126	0.110	0.133	0.123	0.130		0.142
8561	0.065	0.072	0.118			0.111	0.124
8564	0.137	0.100	0.113	0.131	0.137	0.148	0.161
8566	0.130	0.114	0.143	0.138	0.123		0.142
8570	0.141	0.105	0.148	0.142	0.149	0.145	0.157
8572	0.099	0.100	0.091	0.104	0.124		
8576	0.053	0.071	0.085			0.109	0.124
8588	0.113	0.089	0.129	0.098	0.125		
8590	0.104	0.106	0.114	0.108	0.117	0.113	0.101
8592	0.055	0.096	0.092			0.125	0.126
8596	0.062	0.084	0.118			0.122	0.101
8600	0.114	0.094	0.093	0.100	0.114	0.106	0.105
8612	0.044	0.086	0.110			0.111	0.084
8613	0.054	0.077	0.099			0.123	0.140
8615	0.124	0.093	0.116	0.096	0.113	0.112	0.120
8619	0.077	0.097	0.134			0.126	0.148
8621	0.150	0.115	0.126	0.119	0.149	0.141	0.165
8626	0.111		0.124	0.156	0.091	0.114	0.077
8628	0.044	0.085	0.054			0.093	0.092
8633	4.298	0.088	4.181			0.115	1.393

Table 27. Infrared area ratios in the regions 917 - 843 cm^{-1} (A5) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.129	0.112	0.150	0.115	0.141	0.149	0.138
8640	0.118	0.093	0.112	0.153	0.114	0.107	0.132
8642	0.084	0.066	0.112			0.120	0.139
8644	0.113	0.077	0.080			0.090	0.105
8650	0.102	0.072	0.094	0.135	0.108	0.106	0.101
8652	0.051	0.065	0.059			0.085	0.114
8656	0.041	0.059	0.080			0.086	0.074
8726	0.042	0.073	0.087			0.104	0.108
8732	0.027	0.057	0.081			0.039	0.103
8734	0.042	0.114	0.083			0.048	0.120
8736	0.044	0.009	0.103			0.079	0.119
8742	0.107	0.073	0.107			0.031	0.101
8744	0.056	0.082	0.088				0.126
8746	0.143	0.093	0.144	0.133	0.134	0.100	0.138
8748	0.136	0.074	0.109			0.128	0.146
8816	0.104	0.093	0.107		0.117	0.118	0.083
8820	0.066	0.094	0.080			0.134	0.154
8827	0.137	0.085	0.118	0.182	0.129	0.143	0.136
8831	0.079	0.066	0.103			0.128	0.139
8833	0.060	0.044	0.101			0.126	0.102
8839	0.101	0.084	0.106			0.105	0.106
8843	0.122	0.077		0.208	0.150	0.151	0.124
8845	0.047	0.083				0.106	0.141

Table 28. Infrared area ratios in the regions 843 - 785 cm^{-1} (A6) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.105	0.060	0.095			0.093	0.112
8513	0.102	0.086	0.092	0.100	0.103		0.096
8515	0.108	0.096	0.093	0.118	0.098	0.103	0.097
8517	0.103	0.069	0.079	0.092	0.083	0.097	0.098
8519	0.079	0.066	0.069	0.075	0.074		0.079
8521	0.098	0.074	0.100			0.102	0.112
8523	0.083	0.065	0.071	0.085	0.112		0.085
8525	0.095	0.073	0.086	0.093	0.092	0.093	0.106
8527	0.112	0.083	0.078			0.097	0.114
8533	0.094	0.072	0.079	0.095	0.101		0.097
8535	0.108	0.074	0.087	0.095	0.106		0.099
8537	0.094	0.068	0.093	0.087	0.090		0.097
8543	0.079	0.062	0.082	0.080	0.079		0.077
8561	0.094	0.063	0.087			0.094	0.104
8564	0.085	0.057	0.075	0.078	0.075	0.071	0.089
8566	0.085	0.061	0.074	0.094	0.075		0.073
8570	0.077	0.052	0.071	0.080	0.080	0.080	0.078
8572	0.082	0.074	0.079	0.094	0.099		
8576	0.089	0.074	0.076			0.106	0.121
8588	0.093	0.074	0.115	0.092	0.102		
8590	0.096	0.079	0.096	0.105	0.091	0.090	0.099
8592	0.068	0.079	0.069			0.069	0.085
8596	0.093	0.074	0.092			0.088	0.129
8600	0.109	0.080	0.104	0.090	0.107	0.095	0.094
8612	0.097	0.073	0.099			0.100	0.111
8613	0.094	0.075	0.087			0.092	0.115
8615	0.101	0.076	0.093	0.091	0.098	0.089	0.107
8619	0.084	0.087	0.093			0.096	0.104
8621	0.103	0.075	0.091	0.090	0.101	0.092	0.102
8626	0.086		0.103	0.135	0.123	0.090	0.066
8628	0.093	0.093	0.087			0.098	0.107
8633	2.004	0.058	2.630			0.078	3.209

Table 28. Infrared area ratios in the regions 843 - 785 cm^{-1} (A6) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.072	0.059	0.070	0.077	0.074	0.083	0.079
8640	0.098	0.078	0.093	0.139	0.107	0.100	0.095
8642	0.094	0.072	0.088			0.079	0.097
8644	0.120	0.071	0.093			0.098	0.113
8650	0.091	0.078	0.099	0.134	0.106	0.100	0.096
8652	0.103	0.072	0.075			0.101	0.105
8656	0.099	0.070	0.090			0.094	0.117
8726	0.100	0.089	0.108			0.122	0.117
8732	0.084	0.079	0.091			0.101	0.119
8734	0.090	0.064	0.072			0.092	0.109
8736	0.094	0.068	0.091			0.112	0.123
8742	0.106	0.081	0.100			0.081	0.114
8744	0.098	0.077	0.085				0.113
8746	0.082	0.056	0.073	0.076	0.081	0.059	0.085
8748	0.076	0.055	0.081			0.067	0.094
8816	0.088	0.070	0.085		0.094	0.092	0.074
8820	0.079	0.080	0.079			0.088	0.116
8827	0.082	0.060	0.095	0.119	0.086	0.096	0.076
8831	0.091	0.064	0.087			0.085	0.105
8833	0.064	0.053	0.071			0.094	0.082
8839	0.076	0.069	0.088			0.099	0.105
8843	0.082	0.055		0.120	0.095	0.088	0.065
8845	0.082	0.067				0.101	0.118

Table 29. Infrared area ratios in the regions 785 - 687 cm^{-1} (A7) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.382	0.211	0.269			0.263	0.308
8513	0.306	0.268	0.257	0.276	0.273		0.332
8515	0.340	0.259	0.267	0.338	0.254	0.311	0.364
8517	0.319	0.254	0.262	0.288	0.295	0.272	0.405
8519	0.309	0.296	0.271	0.309	0.263		0.348
8521	0.359	0.274	0.196			0.288	0.367
8523	0.304	0.208	0.272	0.267	0.303		0.300
8525	0.274	0.240	0.333	0.295	0.312	0.387	0.280
8527	0.266	0.260	0.145			0.284	0.254
8533	0.330	0.271	0.270	0.292	0.294		0.326
8535	0.336	0.247	0.325	0.304	0.345		0.321
8537	0.299	0.248	0.302	0.274	0.272		0.346
8543	0.298	0.254	0.281	0.287	0.262		0.352
8561	0.339	0.220	0.295			0.300	0.305
8564	0.289	0.211	0.225	0.275	0.274	0.250	0.322
8566	0.267	0.232	0.300	0.270	0.248		0.319
8570	0.308	0.285	0.349	0.303	0.310	0.283	0.409
8572	0.305	0.286	0.228	0.296	0.302		
8576	0.346	0.235	0.250			0.330	0.375
8588	0.306	0.249	0.338	0.299	0.329		
8590	0.283	0.309	0.340	0.310	0.265	0.291	0.329
8592	0.362	0.222	0.144			0.305	0.349
8596	0.393	0.271	0.279			0.319	0.327
8600	0.346	0.284	0.283	0.261	0.316	0.300	0.253
8612	0.393	0.293	0.269			0.268	0.289
8613	0.423	0.235	0.262			0.280	0.354
8615	0.417	0.288	0.363	0.316	0.306	0.407	0.315
8619	0.286	0.201	0.227			0.265	0.334
8621	0.263	0.224	0.225	0.269	0.290	0.287	0.248
8626	0.315		0.321	0.074	0.367	0.354	0.300
8628	0.337	0.246	0.156			0.269	0.299
8633	2.577	0.221	2.399			0.286	2.200

Table 29. Infrared area ratios in the regions 785 - 687 cm^{-1} (A7) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.320	0.234	0.380	0.273	0.288	0.283	0.297
8640	0.354	0.251	0.350	0.015	0.282	0.270	0.296
8642	0.301	0.187	0.242			0.305	0.322
8644	0.300	0.280	0.132			0.322	0.296
8650	0.339	0.191	0.211	0.002	0.242	0.234	0.269
8652	0.252	0.148	0.206			0.235	0.297
8656	0.323	0.146	0.230			0.228	0.258
8726	0.295	0.222	0.306			0.301	0.300
8732	0.365	0.209	0.304			0.360	0.340
8734	0.348	0.294	0.291			0.319	0.235
8736	0.356	0.205	0.295			0.282	0.351
8742	0.261	0.205	0.303			0.257	0.262
8744	0.357	0.205	0.282				0.254
8746	0.356	0.232	0.361	0.281	0.285	0.231	0.320
8748	0.378	0.176	0.271			0.343	0.288
8816	0.193	0.191	0.202		0.197	0.196	0.223
8820	0.241	0.143	0.092			0.242	0.278
8827	0.293	0.179	0.364	-0.017	0.264	0.261	0.262
8831	0.298	0.118	0.181			0.246	0.242
8833	0.200	0.174	0.142			0.175	0.159
8839	0.337	0.213	0.258			0.275	0.245
8843	0.286	0.224		0.010	0.286	0.303	0.295
8845	0.346	0.231				0.303	0.348

Table 30. Infrared area ratios in the regions 1325 - 1281 cm^{-1} (A8) of the virgin asphalts, recovered asphalts, and laboratory exposure residues.

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8509	0.030	0.021	0.025			0.025	0.027
8513	0.026	0.021	0.023	0.026	0.023		0.028
8515	0.028	0.022	0.024	0.032	0.019	0.032	0.032
8517	0.030	0.020	0.027	0.028	0.019	0.029	0.033
8519	0.029	0.027	0.027	0.032	0.024		0.034
8521	0.031	0.024	0.036			0.032	0.030
8523	0.026	0.020	0.021	0.025	0.021		0.029
8525	0.023	0.020	0.027	0.027	0.024	0.034	0.036
8527	0.029	0.022	0.028			0.025	0.027
8533	0.028	0.022	0.026	0.028	0.027		0.028
8535	0.027	0.024	0.028	0.028	0.035		0.032
8537	0.028	0.019	0.026	0.026	0.021		0.030
8543	0.025	0.023	0.021	0.029	0.023		0.031
8561	0.028	0.021	0.030			0.030	0.037
8564	0.026	0.018	0.023	0.028	0.023	0.028	0.031
8566	0.026	0.022	0.028	0.024	0.023		0.029
8570	0.028	0.026	0.033	0.035	0.028	0.033	0.035
8572	0.023	0.024	0.025	0.029	0.032		
8576	0.027	0.023	0.030			0.030	0.044
8588	0.022	0.019	0.040	0.032	0.034		
8590	0.025	0.024	0.031	0.123	0.028	0.028	0.029
8592	0.032	0.024	0.037			0.033	0.039
8596	0.030	0.021	0.036			0.030	0.021
8600	0.029	0.023	0.028	0.030	0.030	0.027	0.030
8612	0.029	0.021	0.028			0.026	0.028
8613	0.034	0.021	0.026			0.027	0.034
8615	0.031	0.022	0.029	0.025	0.025	0.027	0.035
8619	0.022	0.020	0.028			0.026	0.033
8621	0.024	0.021	0.021	0.028	0.027	0.027	0.029
8626	0.025		0.032	0.024	0.032	0.028	0.029
8628	0.028	0.022	0.029			0.029	0.026
8633	10.256	0.025	5.187			0.031	8.385

Table 30. Infrared area ratios in the regions 1325 - 1281 cm^{-1} (A8) of the virgin asphalts, recovered asphalts, and laboratory exposure residues (continued).

FHWA #	VIR	REC	TFO	RTFO	FAD	RFAD	SSD
8637	0.028	0.026	0.041	0.025	0.027	0.029	0.036
8640	0.030	0.025	0.031	0.028	0.025	0.024	0.029
8642	0.027	0.015	0.032			0.028	0.027
8644	0.032	0.023	0.033			0.033	0.034
8650	0.025	0.005	0.023	0.020	0.025	0.022	0.024
8652	0.024	0.017	0.020			0.024	0.032
8656	0.026	0.016	0.022			0.028	0.023
8726	0.027	0.021	0.031			0.025	0.037
8732	0.027	0.020	0.028			0.033	0.035
8734	0.026	0.024	0.026			0.027	0.025
8736	0.025	0.025	0.030			0.028	0.032
8742	0.024	0.021	0.026			0.026	0.020
8744	0.028	0.021	0.029				0.031
8746	0.032	0.026	0.036	0.027	0.026	0.020	0.035
8748	0.036	0.024	0.041			0.028	0.034
8816	0.016	0.016	0.022		0.023	0.022	0.024
8820	0.018	0.013	0.025			0.024	0.030
8827	0.027	0.016	0.032	0.023	0.026	0.030	0.029
8831	0.022	0.013	0.021			0.024	0.026
8833	0.017	0.012	0.017			0.024	0.022
8839	0.026	0.020	0.027			0.028	0.027
8843	0.023	0.019		0.030	0.023	0.028	0.032
8845	0.028	0.018				0.025	0.038

Table 31. Physical, thermal, and molecular size data of Georgia virgin asphalts.

FHWA	B*=2 D=1	PEN 77	PEN 60	VIS 140	VIS 275	VTS	PVN	P1/P2	Tpk2	LMS	SMS
8658	1	66	23	3750	616	-3.458	-0.051	1.7	427	34.33	23.90
8660	2	70	22	3353	593	-3.445	-0.070	1.7	427	33.15	25.92
8662	2	68	22	3532	591	-3.468	-0.064	1.9	428	27.16	26.22
8664	1	74	23	1901	375	-3.591	-0.564	1.6	450	15.07	37.18
8666	1	77	25	2216	410	-3.578	-0.343	1.7	436	19.97	32.37
8668	2	76	24	2427	453	-3.533	-0.270	1.6	430	21.38	30.83
8670	1	71	24	3403	596	-3.447	-0.032	1.6	419	24.87	27.03
8672	1	75	24	2265	403	-3.601	-0.363	1.4	435	18.38	33.61
8674	1	67	20	2161	398	-3.593	-0.586	1.4	459	13.66	38.06
8676	1	74	25	2199	393	-3.610	-0.414	1.4	452	15.10	37.22
8678	1	73	25	2180	389	-3.615	-0.445	1.7	455	13.80	38.45
8680	2	70	23	3518	591	-3.466	-0.021	1.7	428	23.30	28.42
8682	1	70	23	2599	409	-3.644	-0.330	1.5	458	17.04	35.58
8684	2	72	23	3397	582	-3.465	-0.011	1.7	425	24.38	27.64
8686	1	71	24	2183	381	-3.633	-0.487	1.3	455	16.04	36.23
8688	2	66	19	2187	403	-3.587	-0.597	1.6	460	12.23	38.61
8690	1	67	22	2147	392	-3.603	-0.593	1.4	459	13.12	37.71
8692	1	75	24	1758	376	-3.557	-0.624	1.4	457	13.12	37.96
8694	2	69	25	2027	369	-3.630	-0.606	1.4	461	12.05	36.54
8696	2	68	22	2183	404	-3.584	-0.553	1.4	447	13.72	36.64
8698	2	66	21	1941	369	-3.613	-0.718	1.4	463	20.43	35.80
8700	1	69	25	2292	410	-3.592	-0.481	1.6	451	12.79	38.66
8702	2	63	22	3214	496	-3.570	-0.280	1.4	448	27.56	29.51
8704	2	66	22	2332	401	-3.617	-0.532	1.4	458	12.49	37.18

* B = virgin asphalts used in pug mill (batch) operations.
D = virgin asphalts used in drum dryer operations.

Table 32. Infrared data of Georgia virgin asphalts.

FHWA #	A1	A2	A3	A4	A5	A6	A7	A8
8658	-0.098	0.463	0.046	-0.026	0.082	0.113	0.392	0.028
8660	-0.013	0.412	0.031	0.071	0.063	0.078	0.335	0.022
8662	-0.025	0.408	0.034	0.086	0.059	0.084	0.333	0.022
8664	-0.099	0.409	-0.001	0.071	0.118	0.110	0.359	0.033
8666	-0.058	0.446	0.016	0.036	0.101	0.104	0.329	0.026
8668	-0.029	0.428	0.025	0.068	0.087	0.075	0.325	0.022
8670	-0.023	0.432	0.032	0.101	0.064	0.085	0.286	0.023
8672	-0.011	0.408	0.017	0.124	0.097	0.082	0.262	0.021
8674	-0.030	0.363	0.010	0.143	0.111	0.091	0.287	0.026
8676	-0.010	0.357	0.019	0.165	0.111	0.080	0.259	0.019
8678	-0.013	0.392	0.012	0.155	0.095	0.081	0.258	0.020
8680	-0.001	0.472	0.034	0.042	0.063	0.087	0.280	0.023
8682	-0.061	0.387	-0.005	0.145	0.108	0.095	0.300	0.030
8684	-0.026	0.440	0.023	0.097	0.060	0.086	0.294	0.026
8686	-0.035	0.360	0.014	0.154	0.109	0.085	0.288	0.024
8688	-0.031	0.360	0.002	0.150	0.106	0.090	0.298	0.024
8690	-0.048	0.371	-0.003	0.175	0.097	0.090	0.294	0.024
8692	-0.053	0.380	-0.010	0.158	0.106	0.089	0.306	0.024
8694	-0.051	0.402	0.001	0.096	0.108	0.086	0.330	0.029
8696	-0.023	0.356	0.008	0.145	0.092	0.075	0.325	0.023
8698	-0.047	0.386	-0.003	0.123	0.109	0.081	0.327	0.024
8700	-0.035	0.364	0.010	0.146	0.105	0.087	0.298	0.024
8702	0.047	0.397	0.016	0.042	0.116	0.075	0.285	0.022
8704	-0.030	0.387	-0.002	0.150	0.114	0.081	0.274	0.026

Table 33. Physical, thermal, and molecular size data of Georgia asphalt residues recovered from drum dryer or pug mill (batch) operations.

FHWA	B^{*}=2		VIS 140		P1/P2		TEMP	PVN		SMS
	D=1	PEN 77		VIS 275		Tpk2	SUSCEPT		LMS	
8658	1	38	12723	847	2.1	422	-3.665	0.274	37.75	23.16
8660	2	38	11140	1163	0.6	431	-3.390	0.150	40.46	20.54
8662	2	30	14734	1157	1.5	438	-3.492	0.058	39.69	20.87
8664	1	30	15814	1229	1.7	422	-3.474	0.122	34.82	24.85
8666	1	33	13015	995	1.3	434	-3.556	0.084	33.01	26.66
8668	2	36	10467	934	1.5	430	-3.525	0.011	31.93	27.04
8670	1	33	16760	1231	1.7	425	-3.493	0.316	35.47	23.76
8672	1	33	13629	896	1.7	436	-3.648	0.126	32.03	27.27
8674	1	25	13639	826	1.1	455	-3.708	-0.267	23.73	33.46
8676	1	31	15310	832	1.3	448	-3.743	0.141	27.20	31.25
8678	1	29	31889	1202	1.6	459	-3.725	0.705	31.53	27.65
8680	2	37	11599	1118	1.6	425	-3.432	0.148	28.63	27.01
8682	1	29	19976	948	1.6	458	-3.738	0.284	26.03	32.19
8684	2	33	11494	786	1.5	453	-3.685	-0.030	26.36	31.90
8686	1	32	14256	843	1.2	451	-3.708	0.122	24.09	32.48
8688	2	25	18036	930	1.1	454	-3.717	-0.021	23.89	32.46
8690	1	24	27337	1130	1.2	455	-3.718	0.288	25.85	29.77
8694	2	28	10924	677	1.4	452	-3.780	-0.309	21.41	33.10
8696	2	33	8088	1161	1.4	453	-3.277	-0.352	22.99	32.47
8698	2	27	22128	1180	1.7	465	-3.617	0.271	34.06	26.30
8700	1	21	27898	1161	1.5	460	-3.705	0.117	33.40	26.05
8702	2	25	20864	1057	2.0	443	-3.675	0.108	36.29	32.94
8704	2	31	9930	769	1.2	454	-3.649	-0.253	22.61	31.88

B^{*} = recovered residues from pug mill (batch) operations.

D^{*} = recovered residues from drum dryer operations.

Table 34. Infrared data of georgia asphalt residues recovered from drum dryer or pug mill (batch) operations.

FHWA #	A1	A2	A3	A4	A5	A6	A7	A8
8658	-0.012	0.258	-0.005	0.514	-0.011	0.068	0.172	0.017
8660	-0.050	0.396	0.029	0.182	0.061	0.086	0.271	0.025
8662	-0.053	0.392	0.034	0.197	0.062	0.082	0.264	0.023
8664	-0.043	0.474	0.023	0.161	0.054	0.077	0.230	0.024
8666	-0.019	0.508	0.018	0.121	0.089	0.076	0.182	0.024
8668	-0.029	0.393	0.023	0.221	0.081	0.088	0.200	0.023
8670	-0.046	0.482	0.033	0.159	0.056	0.078	0.214	0.024
8672	0.010	0.364	0.012	0.206	0.090	0.081	0.217	0.021
8674	-0.002	0.366	0.008	0.185	0.105	0.080	0.235	0.023
8676	0.026	0.389	0.016	0.179	0.097	0.077	0.198	0.019
8678	0.005	0.361	0.004	0.157	0.096	0.081	0.272	0.024
8680	-0.024	0.404	0.037	0.137	0.065	0.090	0.267	0.023
8682	-0.016	0.386	0.009	0.183	0.095	0.083	0.236	0.024
8684	-0.022	0.390	-0.011	0.338	0.045	0.059	0.179	0.021
8686	-0.052	0.489	0.011	0.185	0.089	0.063	0.192	0.024
8688	-0.007	0.354	0.006	0.175	0.106	0.074	0.270	0.022
8690	-0.006	0.407	0.002	0.155	0.094	0.079	0.244	0.026
8692	0.019	0.324	0.002	0.185	0.101	0.081	0.263	0.024
8694	0.015	0.302	0.009	0.277	0.086	0.076	0.214	0.021
8696	-0.003	0.352	-0.004	0.220	0.086	0.078	0.249	0.022
8698								
8700	0.039	0.352	0.001	0.229	0.093	0.066	0.197	0.023
8702	0.073	0.348	0.017	0.162	0.092	0.063	0.226	0.020
8704	-0.006	0.328	0.006	0.204	0.090	0.070	0.287	0.020

Appendix B

FAD Procedure

This is Forced Air Distillation (FAD) procedure and apparatus used to obtain FAD residues from virgin asphalts.

I. Apparatus

  A. Glassware

    1. Flask
      1000 ml capacity
      3 necks in line
      all 24/40 ground glass female joints
    2. Gas inlet tube
      with hose connector
      inner tube 7.5 cm beyond bottom of joint
      with male 24/40 joint
    3. Thermometer adapter
      24/40 to 10/30
      bushing type
    4. Gooseneck condenser
    5. 3 way connecting tube
      all 24/40 joints
      female at top; 2 males at bottom
      side tube at 109 degree angle
    6. Receiver flask
      50 to 100 ml spherical
      24/40 female joint at top
    7. Bent adapter with take off
      female 24/40 at top
      male 24/40 at bottom
      hose connector at side
      109 degree bend angle
      inner tube length 17 cm from bottom of male joint
    8. Adapter
      24/40 to 29/42
      bushing type
    9. Bubbler tube trap
      29/42 female joint at top
    10. Thermometer

-4 to 680 °F (-20 to 360 °C)range
1 degree divisions

B. Other hardware
  1. Heating mantle
    752 °F (400 °C) maximum
    to fit 1000 ml flask
  2. Air drying apparatus
    with silica gel desiccant
  3. Dewar
  4. Balance
  5. Cheesecloth and form fitting mantle for 1000 ml flask
  6. Gas regulator for compressed air cylinder
  7. Remote thermocouple thermometer
  8. Flow meter with needle valve

C. Supplies
  1. Cylinder of high purity compressed air
  2. HPLC grade isooctane
  3. Hi-vac stopcock grease
  4. Storage bottles
    metal foil lined caps
  5. Asphalt cement

II. Procedure

A. Sampling
  1. If asphalt is in extra wide mouth container
    a. Cut off top inch of asphalt using a heated spatula knife.
    b. Scoop asphalt into beaker on a hot plate.
    c. After asphalt becomes soft enough to flow (no more than 60 minutes), pour 74 to 76 g into preweighed 1000 ml distillation flask.
  2. If cannot use spatula scoop
    a. Place container with loose fitting cap into (617 °F (325 °C) oven for less than 60 minutes (until liquified).
    b. Swirl container to evenly distribute contents.
    c. Pour into beaker on hot plate.
    d. Pour 74 to 76 g from beaker into preweighed 1000 ml distillation flask.

B. Testing

1. Pretest set up
    a. Connect air cylinder to desiccant tube, and desiccant tube to flow meter.
    b. Place thermocouple probe in mantle near heating coils.
    C. set flask with sample on mantle and turn setting to 20 percent ("2" on control mantle) for 15 to 30 minutes.
    d. Add 40 ml HPLC grade isooctane to bubbler tube and insert in ice water bath.
    e. Connect glass apparatus (see figure 4). Use Dow Corning Hi vacuum grease for all ground glass joints.
    f. Be sure thermometer bulb touches the asphalt sample without touching the bottom of the flask. If it touches the flask, use another thermometer adapter.
    g. Place top form fitting mantle on flask and wrap the rest of exposed glass with cheese cloth or some other insulator. Cover top of gooseneck condenser.
    h. Turn on air flow to 1.5 l/min. Watch for bubbling action in isooctane trap.
    i. Record current temperature of mantle and asphalt. Also record setting on mantle and time.
    j. Immediately turn mantle to 100%.
2. Pretemperature limit
    a. Turn mantle control down once mantle temperature exceeds 800 to 820 °F (427 to 438 °C). Record time, current temperatures, and setting. Turn control down only one division at a time.
    b. Maintain an 810 to 830 °F (432 to 443 °C) mantle temperature. Record temperatures and time whenever the setting is changed.
    c. As soon as asphalt temperature reaches 644 °F (340 °C) take a reading.
3. at high temperature limit
    a. Adjust mantle setting to ensure asphalt temperature does not exceed the (644 to 680 °F(340 to 360 °C)) limits. Do not change mantle settings more than one division at a time and not without recording the time and temperatures.

b. After 1 hour of the asphalt first reaching 644 °F(340 °C) take a reading and turn off mantle.

C. Post-testing

1. Disassemble apparatus beginning with bubbler end.
2. Remove gooseneck condenser and place aside without allowing any condensates to drip out.
3. Using gloves, take flask off mantle and wight into 3 oz tin.
4. Take 25 ml HPLC isooctane in beaker and extract condensates at least five times with a disposable 2 ml pipette. Store condenser was in a labelled glass bottle with a metal foil lined cap.
5. Wipe the vacuum grease from the inside joint of the isooctane bubbler. Pour the isooctane solution into a storage bottle using an additional 10 ml to wash the tube. The bottle should be labelled and should have a foil lined cap.

III. Cleaning of apparatus

A. 1000 ml flask

1. Place in TCE bath for at least 24 hours.
2. Rinse with TCE.
3. Place in base/EtOH bath for at least 48 hours.
4. Rinse in hot water.
5. Use brush to loosen any residues.
6. Place in dilute HCL bath for at least 4 hours.
7. Rinse three times in distilled water.
8. Dry.
9. If residues remain, start over with step 3.

B. Remaining glassware (except thermometers)

Continue as above, beginning in step 3.

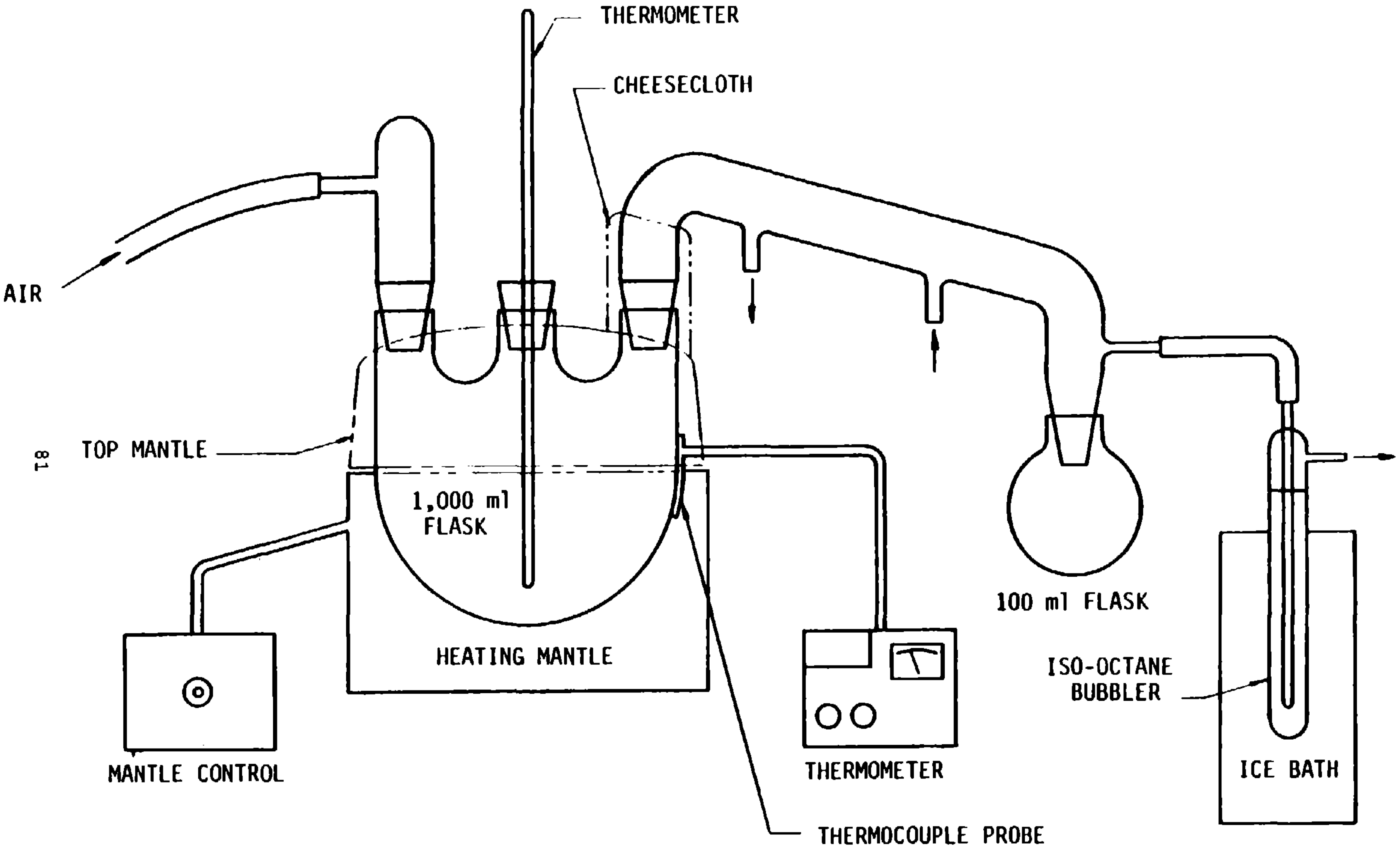

Figure 4. The setup used for the forced air distillation (FAD) procedure.

Appendix C

RFAD Procedure

I. Apparatus.

1. Scissors platform jack.
2. High temperature silicone oil batch.
3. ASTM 8F thermometer or equivalent.
4. Electric hot plate.
5. Buchi rotavapor R.
6. 100 ml round bottom flask, 35/20 T.
7. 1000 ml round bottom flask, 24/40 T.
8. Rheostat.
9. Cylinder of compressed air.
10. Pressure gauge, 250 psig.
11. 45/50 T and 25/40 T connectors.
12. HPLC grade isooctane.
13. Tygon tubing.
14. Stop cock grease.
15. Round aluminum thimbles.
    3/4 in(1.8 cm) diameter.
    1 in(3.0 cm) height.
16. Glass storage bottle (50 ml capacity).

II. Procedure.

Select a representative sample of asphalt to be tested and heat on a hot plate or in a 275 °F (135 °C) oven until completely fluid. Stir the asphalt without incorporating air bubbles and pour 35 grams of the material into a previously weighed 1000 ml round bottom flask (see figure 5). Adjust the rotavapor R angle of rotation until that angle from horizonal is $32 \pm 5°$. It has been found that at a rotavapor set at that angle and at a velocity of 25 RPM, the area of asphalt exposed at one time is equal to that exposed in the rolling thin film oven test.

Immediately connect the above flask to the rotavapor R and raise the previously heated 325 °F (163 °C) oil bath by way of the scissors jack to a position where the maximum amount of the flask is submerged in the bath. Adjust the flow of compressed air through the inlet to a rate of 80 on the gauge or until 2 to 3 bubbles per second are coming out of the outlet tube in the 50 ml isooctane bubbler. The speed of the rotavapor should be adjusted to approximately 25 RPM. Maintain the oil bath temperature at 325 °F (163 °C) and the proper rotation and forced air of the sample for a period of 75 minutes.

At the conclusion of the heating period, disconnect the flask and wipe off all excess oil before pouring the residue in the quick penetration thimbles for testing. Pour the isooctane solution in glass storage bottles for future analysis.

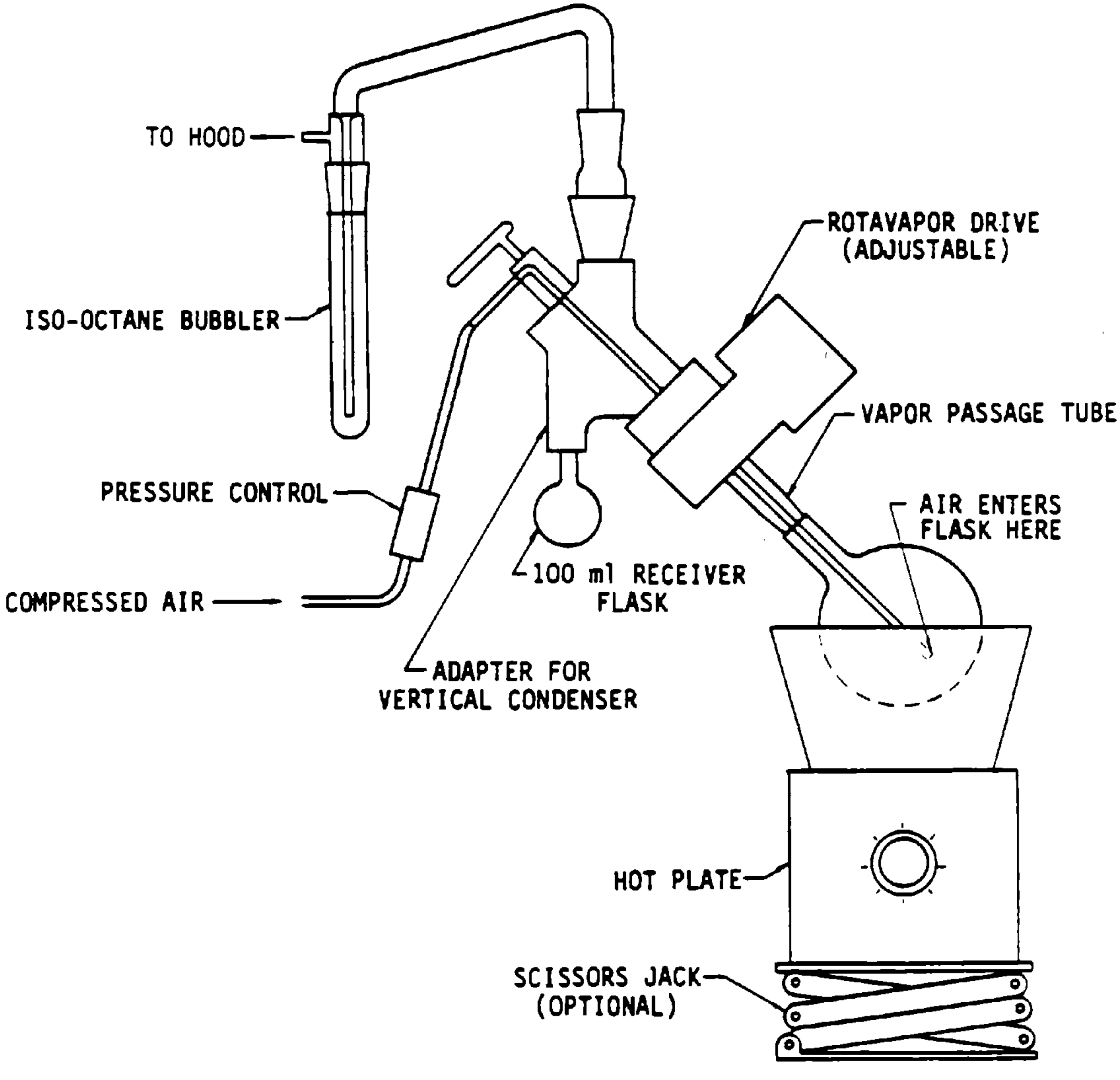

Figure 5. The setup used for the rolling forced air distillation (RFAD) procedure.

Appendix D

HP-GPC Procedure

A high performance gel permeation chromatograph (Waters Associates) was used during this study. It consisted of a solvent reservoir; a high pressure pump unit (Waters 600E); a system controller (Waters 600E); an injector (Rheodyne 7010) fitted with a hundred micro-liter sample loop; a PL gel 100Å precolumn (Rainin); three ultrastryragel columns, (Waters) 1000Å, 500Å, and 100Å columns connected in series; and a UV absorption detector (Schoeffel 700) and in some instances a 990 photodiode array detector (Waters 990). All data were stored and manipulated on an NEC APC IV computer using Waters'baseline 810 and Waters'990 software.

Burdick and Jackson tetrahydrofuran UV grade solvent was dried using standard procedures with sodium and benzophenone and was kept under an argon atmosphere until used.(18) Infrared spectroscopy was used to monitor percent water in the dry THF (0.02 percent max.).

Six asphalts of known large molecular size (LMS), medium molecular size (MMS), and small molecular size content (SMS); used in the HP&R National Pooled-Fund Project, "The Expanded Montana Asphalt Quality Study Using High Pressure Liquid Chromatograph," were obtained from Montana State University.(26) Chromatograms were obtained for these six asphalts with our instrumentation. Vertical lines were positioned in the chromatograms (see figure 3) such that the calculated LMS, MMS, and SMS area percentages agree with those known for these asphalts. The average position (retention time) for these vertical lines were then used to calculate LMS, MMS, and SMS contents of a standard asphalt for use in this study.

The chromatographic system varied in retention times day by day throughout the project due to minor temperature and flow changes. This standard asphalt was used daily to monitor any shifts of the retention time and was used twice each day at the beginning and the end of the day. The difference in retention times of the standard run originally and that run each day of the project was used to adjust the vertical line retention times so that the same retention time (corrected for flow and temperature conditions) is used for area calculations at all times.

Asphalt samples were sampled from cans at an adequate depth so no surface oxidized portion was included for testing. Asphalt samples were made to 0.5 ± 0.05 percent weight by volume in dry THF. This solution was centrifuged at 1500 RPM for 30 minutes. One-hundred microliters of each sample were injected and monitored by UV at 340 nm at a flow rate of 1.0 ml/min. All samples were run with the column temperature at 45 ° ± 0.2 °C. Asphalt samples were randomly selected and run in duplicate each day.

Appendix E

Statistical Treatment

This study used several types of statistical treatments of data depending upon the purpose of its use.

1. The mean (average) of each parameter was calculated using the following equation:(17)

$$\overline{X}_1 = \text{mean (average)} = \frac{\sum X_1}{n_1}$$

where $\overline{X}_1$ = mean (average) of the determinations in set 1

X_1 = each determination in set 1

n_1 = number of determinations in set 1

2. The standard deviation (SD) of each instrumental analysis (DTA, IR, GPC) over a variety of asphalts was determined by analyzing six asphalts (six sets), three determinations each for IR and DTA, two determinations each for GPC. The standard deviation was obtained using the following analysis of variance equation for DTA and IR data:(27)

$$SD = \sqrt{\frac{\sum(\overline{X}_1-X_1)^2 + \sum(\overline{X}_2-X_2)^2 + \ldots + \sum(\overline{X}_6-X_6)^2}{(n_1-1) + (n_2-1) + \ldots + (n_6-1)}}$$

$\overline{X}_1$= mean of triplicate or duplicate determinations in set 1.

X_1= single value of set 1.

n_1= number of determinations in set 1.

The variances (SD^2), although unknown, are assumed to be equal for all asphalt sets (two or three determinations in each set).

3. The acceptable range or repeatability for an analysis is obtained by multiplying the standard deviation for that analysis by a factor depending upon the confidence level and degrees of freedom (DF) for the analysis.(27)

For a 95 percent confidence level:

Degrees of freedom (DF)	Multiplier
6	3.46
12	3.08
50	2.84

DF = k(n-1)
k = number of sets (asphalts)
n = number of determinations in the set (asphalt).

4. The Student's paired t-test was used to compare data of the recovered asphalts from drum dryer mixes with data from various laboratory exposure residues.(21) It was also used to compare data of the recovered asphalts from drum dryer and batch mixes obtained from the State of Georgia.

The null hypothesis was made that the difference between the recovered asphalt data and the laboratory exposure residue data for each analysis is 0 ($u_o = 0$). The following Student's paired t-test equations were used for a two sided t-test.(21)

$$t_o = \frac{\bar{d}}{SD\sqrt{n}}$$

$$\bar{d} = \frac{1}{n} \sum d$$

$$SD^2 = \frac{\sum d^2 - \frac{(\sum d^2)}{n}}{n - 1}$$

d = difference between each recovered asphalt value and the value for the corresponding laboratory exposure residue.

$\bar{d}$ = mean of all differences (d).
$\sum d$ = sum of the differences (d).

n = total number of recovered asphalt or laboratory exposure residue values.

$\sum d^2$ = sum of all squared differences (d^2).

Assuming a 95 percent confidence level (a = 0.025) and if $-t_{.025,n-1} \leq t_o \leq t_{.025,n-1}$, the hypothesis cannot be rejected, or there is no difference between recovered asphalt and laboratory exposure residue values for the analysis used. If $t_o > t_{.025,n-1}$ or $t_o < -t_{.025,n-1}$, then the hypothesis is rejected, or, there is a significant difference between the recovered asphalt and laboratory exposure residue values for the analysis and laboratory exposure data used.

5. Procedures for the determination of outliers (Dixon's r test).(28)

Arrange the data in ascending order $X_1 \ldots X_n$. If the suspected outlier is the smallest value (X_1), calculate r using equation 1. If the suspected outlier is the largest value (X_n), calculate r using equation 2. These equations are valid if $n \geq 14$.

1. $$r = \frac{X_3 - X_1}{X_{n-2} - X_1}$$

2. $$r = \frac{X_n - X_{n-2}}{X_n - X_3}$$

where X_1 = lowest value of n numbers

X_n = highest value of n numbers

X_3 = 3rd lowest number

X_{n-2} = 3rd highest number

n = total number of data

If the value of r is greater than the corresponding number in table II of ref. 26 for a given n, the suspect outlier is rejected.

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GLOSSARY

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing Materials
P1/P2	Ratios of peak area 1/peak area 2 from the DTA thermogram
DTA	Differential thermal analysis
FAD	Forced air distillation
GPC	Gel permeation chromatography
IR	Infrared (spectroscopy)
LMS	Large molecular size
MMS	Medium molecular size
Pen	Penetration
PVN_{140}	Penetration viscosity number using Pen at 77°F (25°C) and Vis at 140°F (60°C)
REC	Recovered asphalt
RFAD	Revolving forced air distillation
RTFO	Rolling thin film oven
SMS	Small molecular size
SSD	Small scale steam distillation
VTS	Viscosity temperature susceptibility using viscosities at 140 °F (60 °C) and 275 °F (135 °C)
TFO	Thin film oven
THF	Tetrahydrofuran
Tpk2	Maximum temperature at 2nd (high temperature) peak in the DTA thermogram
VIR (V)	Virgin asphalt
Vis	Viscosity