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CUTBACK ASPHALT...
AND ASPHALT CEMENT
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1

REPORT

NONMETHANE VOLATILE ORGANIC EMISSIONS FROM ASPHALT CEMENT AND LIQUEFIED ASPHALTS

Air Quality Assessment Section
Environmental and Materials Sciences Division
Midwest Research Institute

DRAFT

FINAL REPORT

December 8, 1978

EPA Contract No. 68-02-2524

MRI Project No. 4305-L

Prepared for

Mr. Thomas F. Lahre
Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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by

Ralph M. Keller

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PREFACE

This report was prepared for the Environmental Protection Agency (Mr. Thomas F. Lahre, Project Officer) to summarize the results of experiments carried out under Work Assignments 2 and 4 of EPA Contract No. 68-02-2524. The work was performed in the Environmental and Materials Sciences Division of Midwest Research Institute, under the supervision of Dr. Chatten Cowherd, Head, Air Quality Assessment Section. Dr. Ralph Keller served as project leader and was the author of this report. He was assisted by Mr. Russel Bohn.

Approved for:

MIDWEST RESEARCH INSTITUTE

A handwritten signature in cursive script, appearing to read "L. J. Shannon".

L. J. Shannon, Director
Environmental and Materials
Sciences Division

December 8, 1978

SUMMARY

Several experiments were conducted on laboratory-prepared samples of asphalt cement, liquefied asphalts, and field-obtained samples of asphalt pavement to determine the total nonmethane volatile organic emissions and the characteristics of the emission rates expected from asphalt materials. Four types of asphalt were studied. They were: asphalt cement, emulsified asphalt, rapid-cure cutback asphalt, and medium-cure cutback asphalt. Slow-cure cutback asphalt was not tested.

It was found that all types emit nonmethane organics at rates which are dependent on the temperature and age of the asphalts. Asphalt cement and emulsified asphalts exhibit gradually decreasing emission rates averaging less than $0.02 \mu\text{g}$ of organics per gram of asphalt per minute after the first 48 hr of curing. The cutback asphalts initially have much larger emission rates which taper off to rates comparable with asphalt cement after 3 months. In the case of the cutback asphalts, as much as 86% by weight of the rapid-cure diluent and 61% by weight of the medium-cure diluent is lost in the first month after paving. Within 3 months, 95% of the rapid-cure diluent and 71% of the medium-cure diluent may be emitted to the atmosphere. Emission rates may increase by a factor of four as the temperature is increased from 25 to 60°C .

Residual, but low level organic emissions are released from asphalt pavement for up to 4 years. These emissions are generally less than $0.002 \mu\text{g}/\text{min-g}$.

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SECTION 1.0

INTRODUCTION

This report presents the results of a laboratory investigation of volatile organic emissions from the major types of asphalt materials used in constructing and repairing roadways and parking surfaces. These major types of asphalt paving materials are: asphalt cement, emulsified asphalt, and cutback asphalt. These widely used materials contain volatile organics which may contribute to the formation of photochemical oxidants in the atmosphere.

A series of laboratory experiments, which are summarized in Table 1, were designed to measure emission factors for the rate of loss and the total loss of volatile organics from laboratory-prepared samples of asphalt cement and liquefied asphalts, and from pavement samples taken from existing asphalt roads. In the laboratory, these samples were exposed to simulated conditions of outdoor exposure. In addition, experiments were performed to determine (a) the effect of surface fracture on emissions from cured cutback asphalt and (b) the quantity of solvent lost during mixing of cutback asphalts.

Initial experiments consisted of measurements of percentage weight loss versus temperature of milligram-size, laboratory-prepared samples of asphalt cement and liquefied asphalts for the purpose of determining the maximum possible organic losses from asphalt-paving materials. A sample configuration with a high surface to volume ratio was selected in order to eliminate the solid phase resistance to mass transfer to volatile organics.

A second series of experiments involved measurement of organic emissions from cylindrical samples (2-1/4-in. diameter by 1/8-in. thickness) of laboratory-prepared asphalt cement and liquefied asphalts exposed to an air flow across the top surface layer. After these 120-min tests were performed on samples of all three types of asphalt, extended testing over 17 days was conducted. At the end of the 17-day period, the cured surfaces were fractured to determine the effect of surface fracturing on emissions.

TABLE 1. SUMMARY OF EXPERIMENTS CONDUCTED

Purpose of experiment	Duration of experiment	Size of sample	Exposure condition	Measurement frequency	Analytical technique
• Total emissions	120 min	13-70 mg	Nonreactive air elevated temperature	Continuous	Thermogravimetric
• Composition and emission rate	120 min	0.1 mg	Room temperature flowing air	5 min	Gas Chromatograph
• Long-term emission rate	120 min/day for 17 days	3 gm	Room temperature flowing air	5 min	Gas Chromatograph
• Emission characteristics under cured surface perturbations	60 min	3 gm	Room temperature flowing air	5 min	Gas Chromatograph
• Total weight lost	17 days	3 gm	Room temperature	-	Analytical balance
• Diluent losses during initial sample mixing	30 min	10 gm	Elevated temperature	-	Analytical balance
• Total weight lost over long periods	125 days	40-116 gm	Room temperature and elevated temperature	Periodically	Analytical balance
• Emission characteristics of field samples	60 min	185-750 gm	Room temperature and elevated temperature	5 min	Gas Chromatograph
• Emission characteristics under cured surface perturbations	60 min	472-503 gm	Room temperature and elevated temperature	5 min	Gas Chromatograph
• Total emissions due to fracturing	7 days	90-127 gm	Room temperature and elevated temperature	5 min	Gas Chromatograph

A third series of experiments involved the measurement of the weight loss from laboratory-prepared samples of cutback asphalts over a period of 125 days. The sample weights were measured at intervals to record the loss of mass presumably due to the evaporation of organics from the samples. In the latter part of the experiments, the temperature of some of the samples was elevated to 60°C.

A fourth series of experiments involved the measurement of emissions from a limited number of roadway sample plugs (6.9-cm [2.7-in.] diameter and 5.1- to 10.2-cm [2- to 4-in.] in thickness) removed from road beds where medium-cure cutback asphalts were used. Emission rates were determined for these samples under the following conditions: (a) samples at 27°C, (b) samples at 25 to 60°C, (c) samples at 60°C with the surface fractured and (d) totally fragmented samples at 25°C.

This report is structured to present (a) an overview of the experiments (Table 1), (b) a description of the sampling and analytical equipment and (c) a discussion of results of the experiments. Section 3 discusses the results of the experiments on laboratory-prepared samples. Section 4 presents the results of the experiments on field-obtained samples of cutback asphalt pavement. Section 5 compares the results of the various experiments and presents the conclusions of the work.

SECTION 2.0

SAMPLE PREPARATION AND TEST EQUIPMENT

This section describes test procedures for asphalt sample preparation, use of the thermogravimetric analyzer, and the experimental systems for organic emission measurements utilizing gas chromatography (GC).

2.1 SAMPLE PREPARATION - LABORATORY-PREPARED SAMPLES

Asphalt cement and emulsified asphalt samples, in metal quart cans with a 1-in. opening, were provided by Union Asphalt Company of Kansas City, Missouri. Asphalt cement (penetration grade 85/100) was heated in its metal container in a water bath of 100°C (212°F). At this temperature, the asphalt cement was sufficiently fluid to pour from the can. The emulsified asphalt sample was fluid at room temperature and could be poured without preheating.

The cutback asphalts were mixed in the laboratory at the time of the experiment. Asphalts (penetration grades 85/100 and 60/70) were used with the proper diluents to produce rapid-cure and medium-cure cutback asphalts. Diluent proportions were 25, 35, and 45% by volume* depending on the type of cutback used and the diluent proportion desired. Sample sizes ranged from 20 to 40 ml. In order to mix the asphalt cement and diluent, the asphalt cement was heated to 100°C (212°F), and the diluent was heated to just below its boiling point. At the time of pouring, the sample had cooled sufficiently to be held in the hand.

2.2 SAMPLE PREPARATION - FIELD-OBTAINED SAMPLES

The asphalt roadway plugs were obtained from four rural roadways in Pettis County, Missouri. The four roads selected for testing were surfaced in 1977, 1976, 1975, and 1974, respectively. Three plugs were taken from each two-lane roadway surface (road edge, middle of lane, center of road) by using a 3-in. diameter concrete core drill. From the field, the plugs were transported to Midwest Research Institute (MRI), washed, weighed, and the outer surfaces, excluding the top, wrapped tightly in aluminum foil. This eliminated emissions escaping from other than the top of the plug.

* In this report, diluent proportions for cutback asphalts are expressed as percent by volume. Conversions to percent by weight are given in Table B-1.

2.3 THERMOGRAVIMETRIC ANALYSIS

A Perkin Elmer TCS-1 thermogravimetric analyzer was used for the purpose of measuring weight loss of an asphalt sample as a function of temperature. A small quantity (40 to 70 mg) of asphalt cement or liquefied asphalt was transferred into a preweighed sampling pan (1/4-in. diameter by 1/8-in. depth). The pan and sample were loaded into the thermogravimetric balance and an initial weight obtained. The temperature was increased in a prescribed manner and the mass change recorded continuously on strip chart paper. The temperature program was varied three ways: constant temperature, linearly increasing temperature, and cyclic temperature.

2.4 LABORATORY FLOW SYSTEM AND GC ANALYSIS

The laboratory flow system for measuring organic emissions from laboratory-prepared asphalt samples is shown in Figure 1. The sample was placed in a glass jar with dimensions of approximately 2-1/4-in. diameter by 2-1/4-in. height. A 1/8-in. thick layer of asphalt covered the bottom of the jar. The jar lid had either two or three holes drilled into it. One hole served as the clean air intake. The second hole was connected to the intake of a Beckman Model 6800 Total Hydrocarbon Analyzer--an automatic GC instrument with a flame ionization detector. The third hole served as an exhaust port whenever the clean air flow was increased above the GC sampling rate.

The laboratory GC analysis/flow system was modified for sampling the roadway plugs. A 3-in. diameter by 7-in.-high glass jar was used as a sampling chamber. The jar lid had three holes drilled into it. One hole held a temperature sensing thermocouple; another held the sampling line leading to the GC; and the third held the tubing from the zero air supply. The flow rate of the environmental air removed by the GC intake was matched by the clean air entering the jar through the use of a bypass flow system. The bypass system allowed any excess clean air to exit from the clean air line through a water trap which prevented environmental air from entering the sampling system.

The Beckman GC sampled continuously at a predetermined constant rate. For the experiments of Part I, the flow rate was 0.8 liter/min. During the experiments of Part II, the flow rate was 1.25 liters/min. At 5-min intervals, the sample stream was analyzed for concentrations of total hydrocarbons, methane, and carbon monoxide. An example calculation for determining emissions is given in Appendix A.

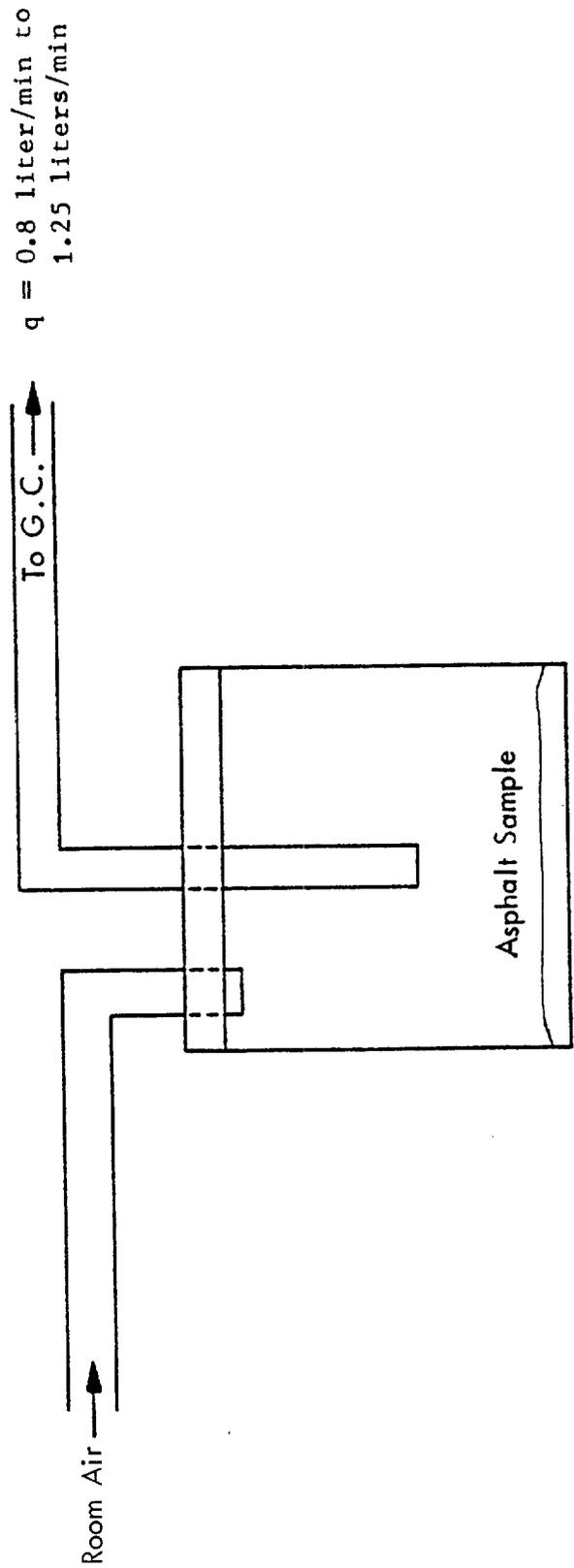


Figure 1. Sample Jar Used in Gas Chromatograph Analyses

SECTION 3.0

RESULTS OF EXPERIMENTS ON LABORATORY-PREPARED SAMPLES OF ASPHALT CEMENT AND LIQUEFIED ASPHALTS

Four sets of experiments were performed on the laboratory-prepared asphalt samples. The first set of experiments measured the total weight losses possible from the various asphalts (thermogravimetric analysis) and the organic emission rates for the initial 2 hr after sample preparation (GC analysis). The second set of experiments measured the organic emission rates over a 17-day period (GC analysis), and the effect of perturbations on the emission rates of the samples on the 17th day (GC analysis). The third set of experiments measured the weight loss of the asphalt samples over 17- and 124-day periods (analytical balance). The fourth set of experiments measured the quantity of asphalt diluent loss in the laboratory as the asphalt cement and diluent were mixed (analytical balance). The results of these experiments are presented in the following subsections.

3.1 THERMOGRAVIMETRIC AND SHORT-TERM GC ANALYSIS

The initial set of experiments using the thermogravimetric and short-term GC analysis indicated (a) total quantities emitted for each asphalt type, (b) the temperature dependence of the emission rates. The emissions consisted entirely of nonmethane organics and water (in the case of emulsified asphalt). A discussion of the results obtained by each analytical method for each type of asphalt follows.

3.1.1 Thermogravimetric

As stated above, the initial experiments consisted of measurement, by thermogravimetric analysis, of the total mass of emissions from samples of the three types of asphalt. Three experimental runs were made for each asphalt type. The cutback asphalts were categorized as to percent (by volume) of diluent. The raw data of the experiment are presented in Appendix B. The graphical representations of the relationships between emissions and the temperatures of the samples are also given in Appendix B.

3.1.1.1 Asphalt Cement--

Asphalt cement was found to emit a small amount of organics with the rate of emission depending on the temperature of the asphalt. An average of 0.36% (derived from Appendix B, Table B-1) of the initial asphalt cement mass was lost when the sample was subjected to temperatures up to 229°C.

The rate of weight loss was found to increase with increasing temperature (as can be seen in Figure B-1 in Appendix B). This phenomena is shown in Figure 2, where the slope of the weight loss curve represents the emission rate. This result indicates that emissions from asphalt pavement will increase with temperature during the day and decrease with temperature during the night in a repetitive manner.

3.1.1.2 Emulsified asphalt--

Emulsified asphalt lost an average of 6.4% of its initial weight during the thermogravimetric tests. Most of this weight loss is attributable to water evaporation. The rate of the weight loss was dependent on the temperature, with the high temperatures resulting in higher emission rates. The higher losses resulted from all of the water being drawn off in a shorter time period. The temperature-weight loss characteristics of emulsified asphalt are shown in Figure B-2 in Appendix B.

3.1.1.3 Cutback asphalts--

The cutback asphalts exhibited weight losses amounting to approximately 5% of the initial sample weight. The exact weight loss percentages for each cutback type are given in Table B-1 in Appendix B. The emission rates were dependent on temperature in a manner similar to those of emulsified asphalt. Examples of weight loss dependency of these samples on temperature may be found in Figures B-3 through B-6.

3.1.2 Short-Term GC Analysis

The results of the short-term GC experiments to determine emission rates of the asphalt types are presented in Table 2. These tests developed emission rates for penetration grade 85/100 asphalt cement, emulsified asphalt, medium-cure asphalt (35% diluent), and rapid-cure asphalt (45% diluent) during the 120 min after initial mixing. The cutback and emulsified asphalt samples were at room temperature during the test period. The asphalt cement sample cooled from its initial temperature of 100°C to room temperature within 30 min.

3.1.2.1 Asphalt cement--

The emission rate of asphalt cement varied from an initial value of 0.17 µg/min-g (at a sample temperature of 100°C) to 0.01 µg/min-g measured 100 min later (at a sample temperature of 25°C) as shown in Tables 2 and 3. The emission rates versus time for asphalt cements are plotted in Figure 3. The asphalt cement emission rate was found to approach a constant value during the final 90 min of the testing period when the temperature had become constant.

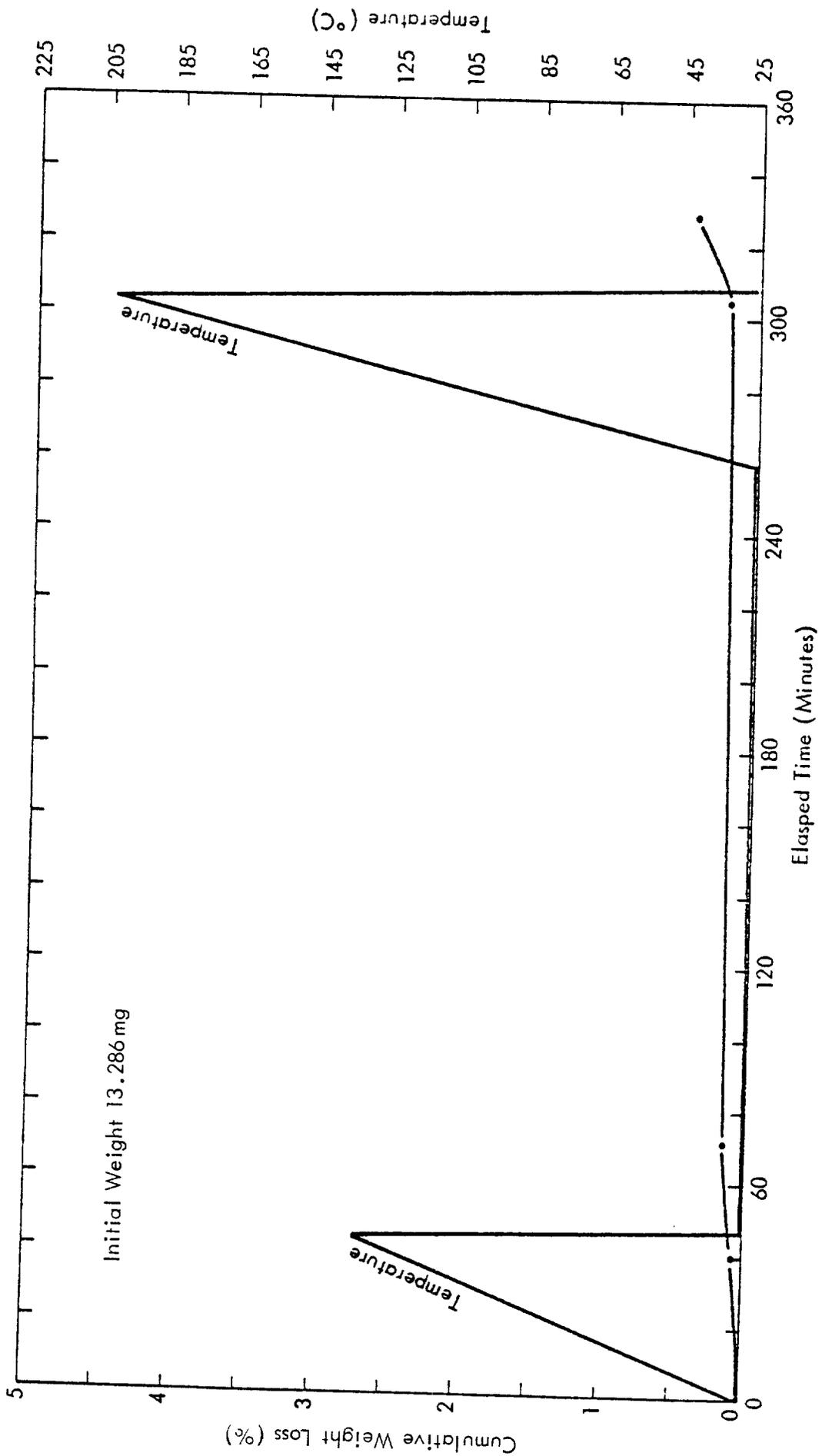


Figure 2. Weight Loss of Penetration Grade 85/100 Asphalt Cement
(Thermogravimetric Analysis)

TABLE 2. EMISSION RATES OF VOLATILE ORGANICS FROM ASPHALT CEMENT
AND LIQUEFIED ASPHALTS (Short-term GC Analysis)

Time (min)	Emission rate ($\mu\text{g}/\text{min-g}$)		Emulsified asphalt	Cutback asphalts		
	Asphalt cement Penetration grade 85/100	Asphalt cement		Medium cure (35% diluent by volume)	Rapid cure (45% diluent by volume)	
0	0.17	0.07	0.07	1289	5,714	
5	0.14	0.05	0.05	995	2,605	
10	0.11	0.04	0.04	816	1,479	
15	0.08	0.04	0.04	666	1,084	
20	0.06	0.03	0.03	561	798	
25	0.05	0.03	0.03	486	597	
30	0.04	0.04	0.04	417	496	
35	0.04	0.04	0.04	359	403	
40	0.03	0.04	0.04	318	327	
45	0.03	0.03	0.03	281	286	
50	0.03	0.03	0.03	261	244	
55	0.02	0.03	0.03	220	173	
60	0.02	0.02	0.02	214	176	
65	0.02	0.02	0.02	193	151	
70	0.02	0.02	0.02	174	143	
75	0.02	0.02	0.02	162	118	
80	0.02	0.02	0.02	156	101	
85	0.02	0.02	0.02	145	76	
90	0.02	0.02	0.02	135	76	
95	0.01	0.02	0.02	127	59	
100	0.01	0.02	0.02	115	50	
105	0.01	0.02	0.02	-	42	
110	0.01	0.02	0.02	-	-	
115	0.01	0.02	0.02	-	-	
120	0.01	0.02	0.02	-	-	
125	0.009	-	-	-	-	

- no data

TABLE 3. SUMMARY OF EMISSION RATES OF VOLATILE ORGANICS FROM ASPHALT CEMENT AND LIQUEFIED ASPHALTS (Short-Term GC Analysis)

Asphalt type	Initial sample mass	Emission rate ($\mu\text{g}/\text{min-g}$) ^{a/}		
		First min	Average	100th min
Asphalt cement	42.81 gm	0.17	0.04	0.01
Emulsified	42.80 gm	0.07	0.03	0.02
Rapid cure (45% diluent)	0.0119 gm	5,700	575	50
Medium cure (35% diluent)	0.1728 gm	1,200	340	100

^{a/} Temperature of asphalt cement decayed from initial value of 100°C to 25°C. Other asphalts held at 25°C throughout experiments.

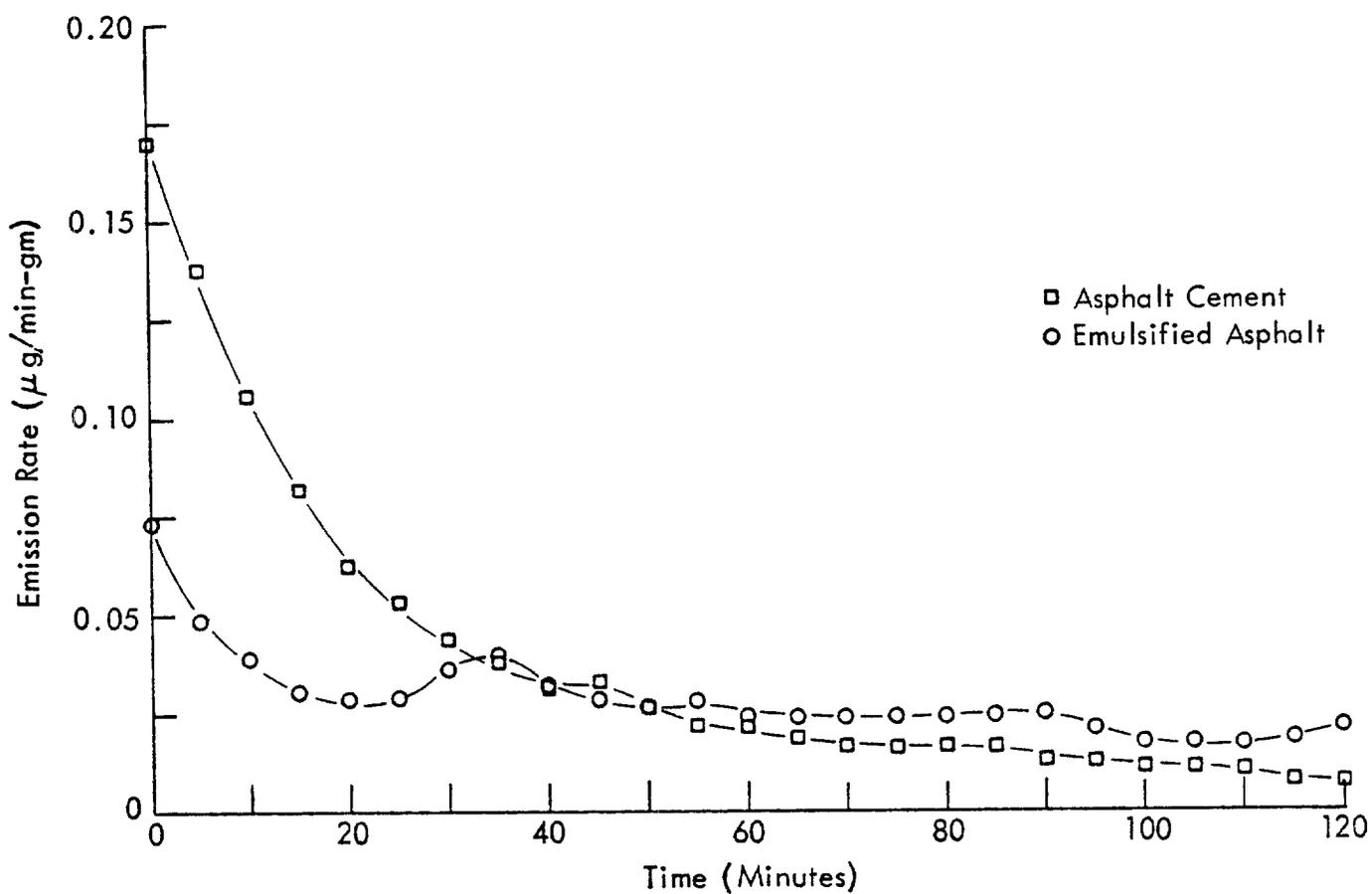


Figure 3. Organic Emission Rates for Asphalt Cement and Emulsified Asphalt (Short-term GC Analysis)

3.1.2.2 Emulsified asphalt--

The GC analysis indicated that most of the 6.4% weight loss determined from the thermogravimetric tests was due to water losses. The organic emission rate was 0.07 $\mu\text{g}/\text{min-g}$ initially and dropped to 0.02 $\mu\text{g}/\text{min-g}$ after 100 min as seen in Tables 2 and 3 and Figure 3. Graphical integration of the data acquired indicates a total weight loss due to organic emissions of $2.7 \times 10^{-4}\%$. The emulsified asphalt used in this testing was reported to contain 35.5% water by weight with no organic diluents added. This would lead one to expect the composition of the emissions to be mostly water. The organic portion of the emissions would be expected to be similar to those of the asphalt cement at room temperature since asphalt cement is used as a base for emulsified asphalt.

3.1.2.3 Cutback asphalts--

Emissions from cutback asphalts consisted of nonmethane organics. The emission rates determined by GC testing of rapid-cure and medium-cure asphalt are shown in Tables 2 and 3 and Figure 4. The emission rates for rapid-cure cutback asphalt (45% diluent) decreased from 5,700 to 50 $\mu\text{g}/\text{min-g}$ after 100 min. The emission rates for medium-cure cutback asphalt (35% diluent) decreased from 1,200 to 100 $\mu\text{g}/\text{min-g}$ after 100 min.

These test results were consistent with expectations. The sharp decrease in emission rate is a result of the curing of the surface forming a resistance layer which impedes the passage of the diluent into the atmosphere. Rapid-cure asphalt should lose a large portion of the diluent quickly, cure quickly, with a resultant drop in the emission rate to a low value. Relative to rapid cure, medium-cure asphalt should lose diluent at a slower rate, take longer to cure, and have relatively higher emission rates for a longer period of time.

The quantity (weight) of diluent loss related to cutback mass and initial diluent mass is shown in Table 4. Note that the thermogravimetric samples were subjected to elevated temperatures up to 150°C while the GC samples were at room temperature.

Emissions from asphalt cement and emulsified asphalt were found to be sufficiently low to warrant no further investigation. Emissions from cutback asphalt were not characterized sufficiently by this part of the program; therefore, longer term experiments were carried out.

3.2 17-DAY GC AND WEIGHT LOSS TESTS

To determine the long-term emission rates and the quantities of diluent loss over a period of days, an experiment was conducted wherein the weight and emission rates of cutback asphalt samples were monitored for a period of 17 days. The weight loss and emission rates for rapid-cure asphalt (45% diluent) and medium-cure asphalt (45% diluent) over a 17-day period (August 7

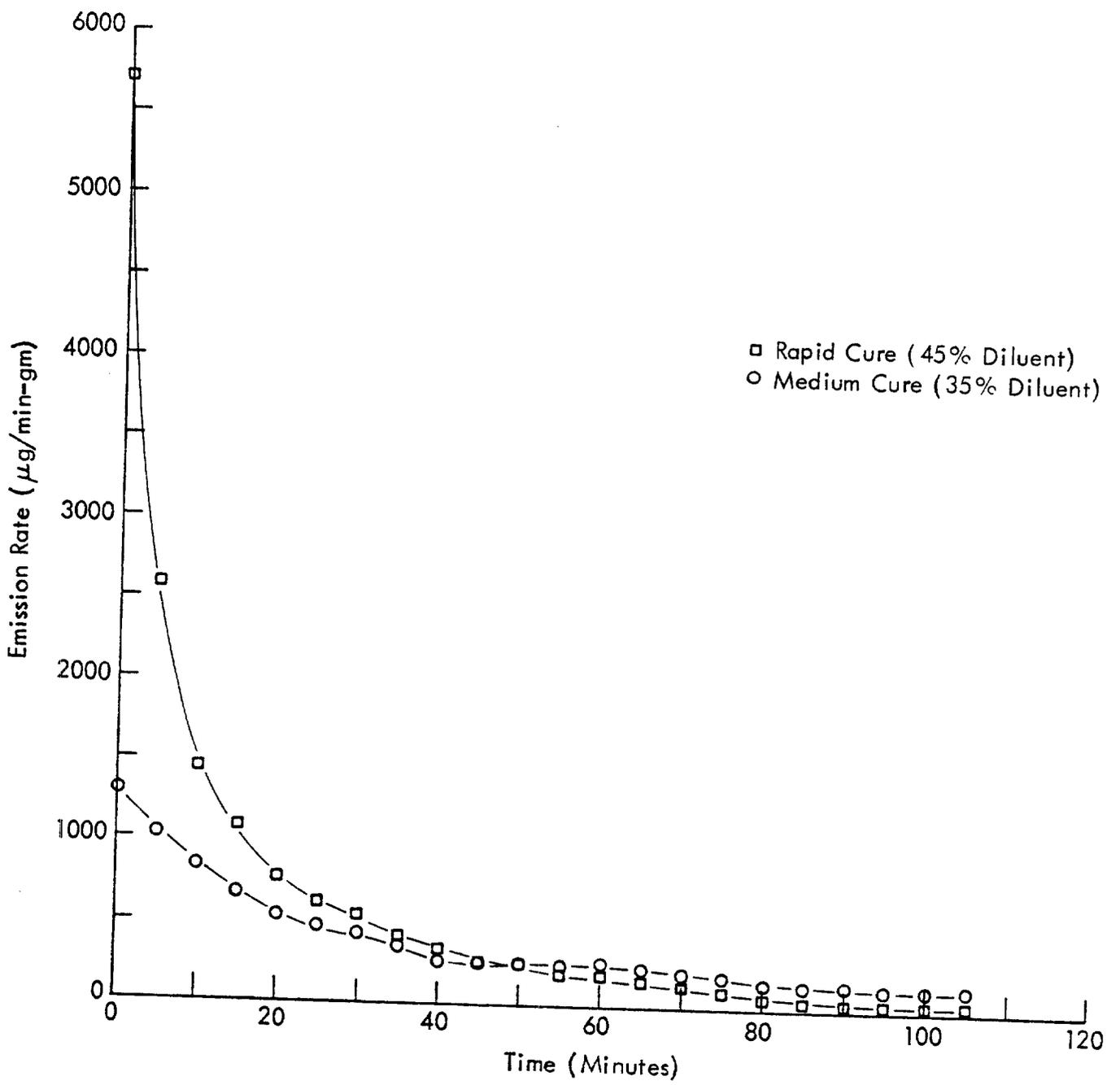


Figure 4. Organic Emission Rates For Rapid Cure And Medium-Cure Cutback Asphalts (Short-term GC Analysis)

TABLE 4. WEIGHT LOSS OF CUTBACK ASPHALTS DURING THE
FIRST 100 MIN OF CURING^{a/}

	Thermogravimetric analysis		G.C. analysis	
	% of Total Weight	% of Diluent Weight	% of Total Weight	% of Diluent Weight
Rapid-cure cutback (45% diluent)	4.7	13	5.7	15
Medium-cure cutback (35% diluent)	6.5	18	3.4	9

a/ The thermogravimetric samples were at elevated temperatures of up to 150°C, while the G.C. analyses were conducted on samples at ambient temperatures.

to 19, 1977) are given in Table 5. The emission rates measured by the GC over this time period are graphically presented in Figure 5. The data that were used to derive the continuous (average) emission rates are presented in Figure 6.

The initial emission rates for the cutback asphalts were similar to those measured during the experiments discussed in Section 3.1 of this report (see Table 3). The emission rates for rapid-cure asphalt were three times those of medium-cure asphalt initially but declined to less than half of those of medium cure on the 17th day.

Referring to Figure 5, the higher emission rates at the beginning of each test than was noted at the end of August 3, may be explained by a resistance film of air above the asphalt. Between testing periods, the jar lids were removed but a stagnant air layer remained above the asphalt. The air layer allowed a uniform concentration gradient to be formed. When the air began to flow over the asphalt during the test, the diluent concentration was depleted in the air and the top layer of the asphalt. Then the resistance of the asphalt to diluent flow began to build, causing the emission rate to decay. As the concentration of the diluent decreased, the resistance effect also decreased.

Because of the stagnant air layer and the varying emission rates during storage, it is not possible to graphically integrate the area beneath the curves in Figure 5 to obtain total emissions. The value obtained would be greater than the mass of diluent found initially in the sample. This phenomenon has also introduced some error in the measured mass loss after a finite time period. It would be reasonable to expect the diluent to be lost at a greater rate in a real situation, since a stagnant air layer would not exist over roads or parking areas.

The continuous emission rates determined over the 17 days are presented in Figure 6. Rapid-cure asphalt emission rates were initially higher than medium-cure asphalt emission rates but dropped below them on the second day. The rapid-cure emission rate appeared to become constant after the 7th day at $1.2 \mu\text{g}/\text{min-g}$. The medium-cure emission rate decreased throughout the test period. After the 7th day, the rate of decrease became constant at $0.47 \mu\text{g}/\text{min-g}$. At this decreasing rate, the medium-cure emission rate would reach the rapid-cure emission rate by the 22 day.

As mentioned previously, while measuring the emission rates, the samples were weighed to determine the mass loss over the 17 days. Table 6 shows the mass loss for each cutback type expressed as the percent of total weight and diluent weight. Rapid-cure emission totaled 86.4% of the initial diluent weight (corrected for mixing losses), while medium-cure emission totaled 60.8%. The limiting values for the percent for the total mass loss should represent the diluent mass percent originally in the sample. Rapid-cure asphalt lost a larger percentage of its total ultimate emissions in the 17-day period than

TABLE 5. ORGANIC EMISSION RATES FOR CUTBACK ASPHALTS (Long-term GC Analysis)

Date	Rapid Cure Asphalt (45% diluent)		Medium Cure Asphalt (35% diluent)	
	Initial Emission Rate ($\mu\text{g}/\text{min-g}$)	Final Emission Rate ($\mu\text{g}/\text{min-g}$)	Initial Emission Rate ($\mu\text{g}/\text{min-g}$)	Final Emission Rate ($\mu\text{g}/\text{min-g}$)
8/ 2 (morning)	2,597	105	786	75
8/ 2 (afternoon)	-	-	-	-
8/ 3	9.2	5.8	23	12.5
8/ 5	4.3	1.0	20	11.3
8/ 9	1.3	1.2	9.6	7.1
8/12	1.5	0.04	3.7	3.1
8/19	1.3	1.2	3.1	2.9

- No data

RC Rapid Cure (45% Diluent)
 MC Medium Cure (35% Diluent)

Note:
 Data were obtained at five minute intervals over the
 two hours of sampling on days shown.

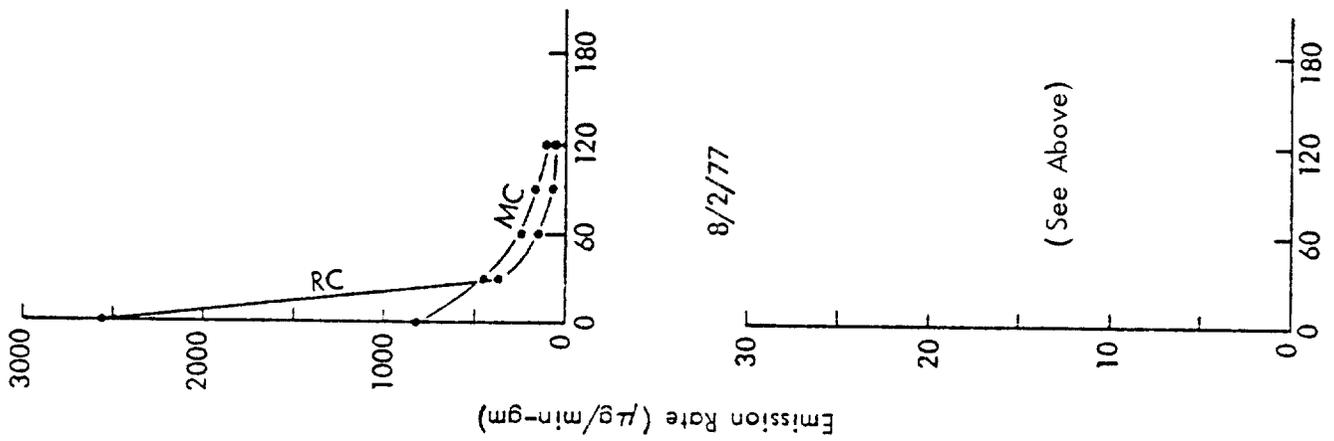


Figure 5. Organic Emission Rates for Outback Asphalts
 (Long-term GC Analysis)

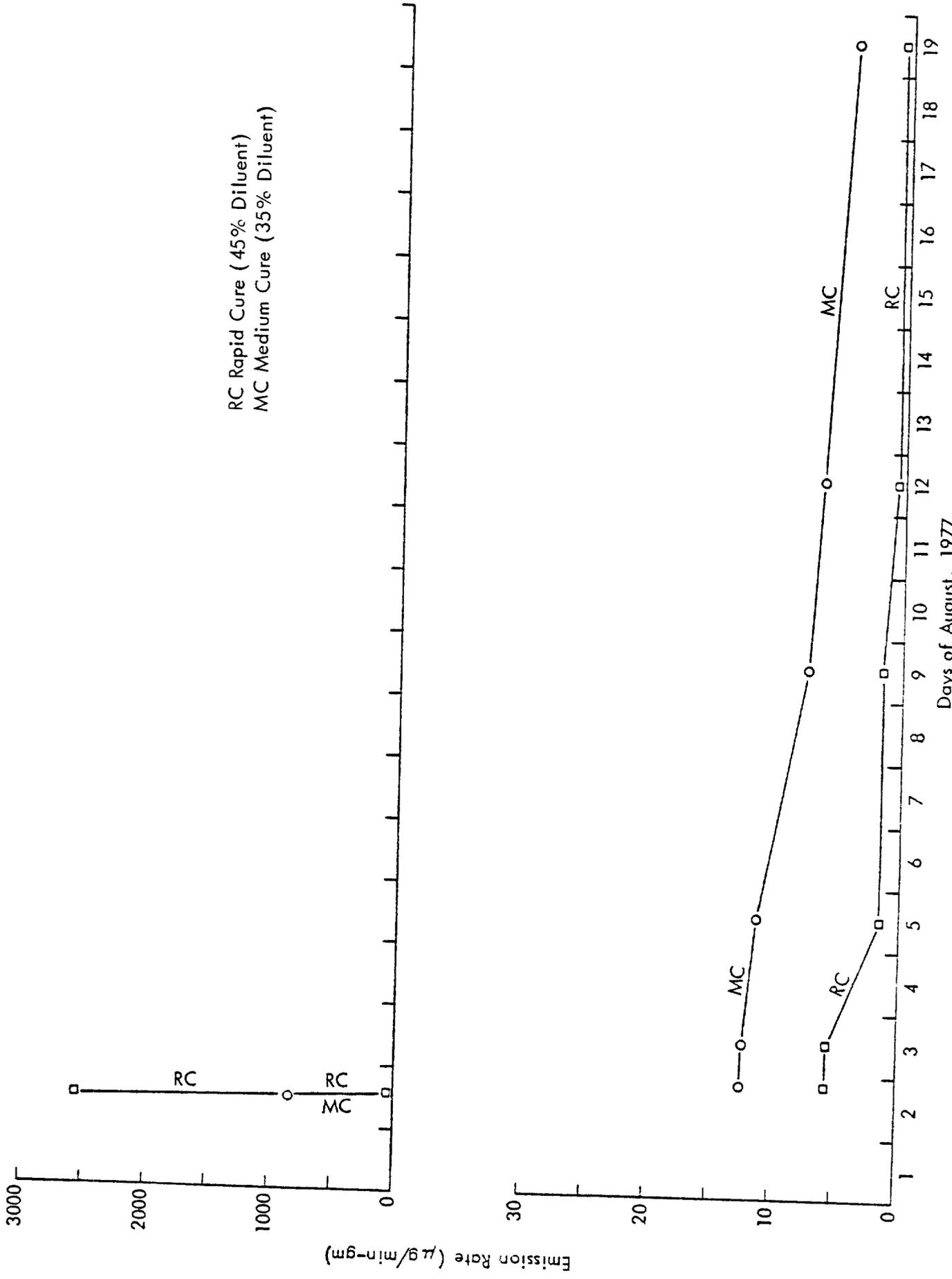


Figure 6. Average Organic Emission Rates for Cutback Asphalts (Long-Term GC Analysis)

medium-cure asphalt. However, the emission rates of rapid cure had approached a small value by the 17th day, while medium-cure emission rates were still sufficient to be causing measurable weight losses, thus indicating that the percentage of total ultimate losses for medium-cure will approach the ultimate losses for rapid cure.

The weights of the samples over the 17 days are presented in graphical form in Figure 7. It can be seen that the decrease in the rapid-cure sample weight is not detectable on the scale used. The cured cutback weight loss rate was 5.7×10^{-3} g/day. On the 17th day, the weight difference was 0.41 g. At the indicated weight loss rates, it would take 72 days for medium-cure emissions to equal those of rapid-cure asphalt. However, since the medium-cure emission rate was decreasing, it is doubtful that the total medium-cure emissions would have exceeded total rapid-cure emission. This indicates that medium-cure asphalt nonmethane organic emission rates remain higher than rapid-cure asphalt emission rates for quite some time, but total emissions for rapid-cure asphalt still exceed the medium-cure asphalt emission.

The emission rate curves presented in Figure 6 were integrated to determine the approximate mass loss to check the agreement with the mass lost shown in Table 6. For rapid cure, the integrated emissions were 17% compared to 32% in Table 6. The medium-cure emissions were 25% by graphical integration and 22% by mass measurement. Since emission rates were averaged or extrapolated from Figure 6 to get a continuous curve for the time period, exact agreement was not expected. The emission rates determined by the two methods agree within a factor of 2 and thus are reasonably comparable.

3.3 LONG-TERM WEIGHT LOSS TEST

A similar experiment was conducted over a longer time period to determine the trend of weight loss for all four asphalt types. For the cutback asphalts, the experiment lasted over 124 days. The asphalt cement and emulsified asphalts were weighed over 68 days. Each asphalt type had duplicate samples in the experiment. The results of the data obtained for the cutbacks are shown in Table 7. The results of the data obtained for the asphalt cement and emulsified asphalts are shown in Table 8.

After 124 days, the rapid-cure asphalt samples had lost an average of 94.8% of the diluent initially in the samples. The emission rate, obtained by dividing the weight loss by the initial sample mass and time, had declined to an average of $0.02 \mu\text{g}/\text{min-g}$ by the 124th day and appeared to still be declining. The data indicate that at least 95% of the diluents added are lost from rapid-cure asphalt and that some organic emissions are still occurring after 124 days of curing.

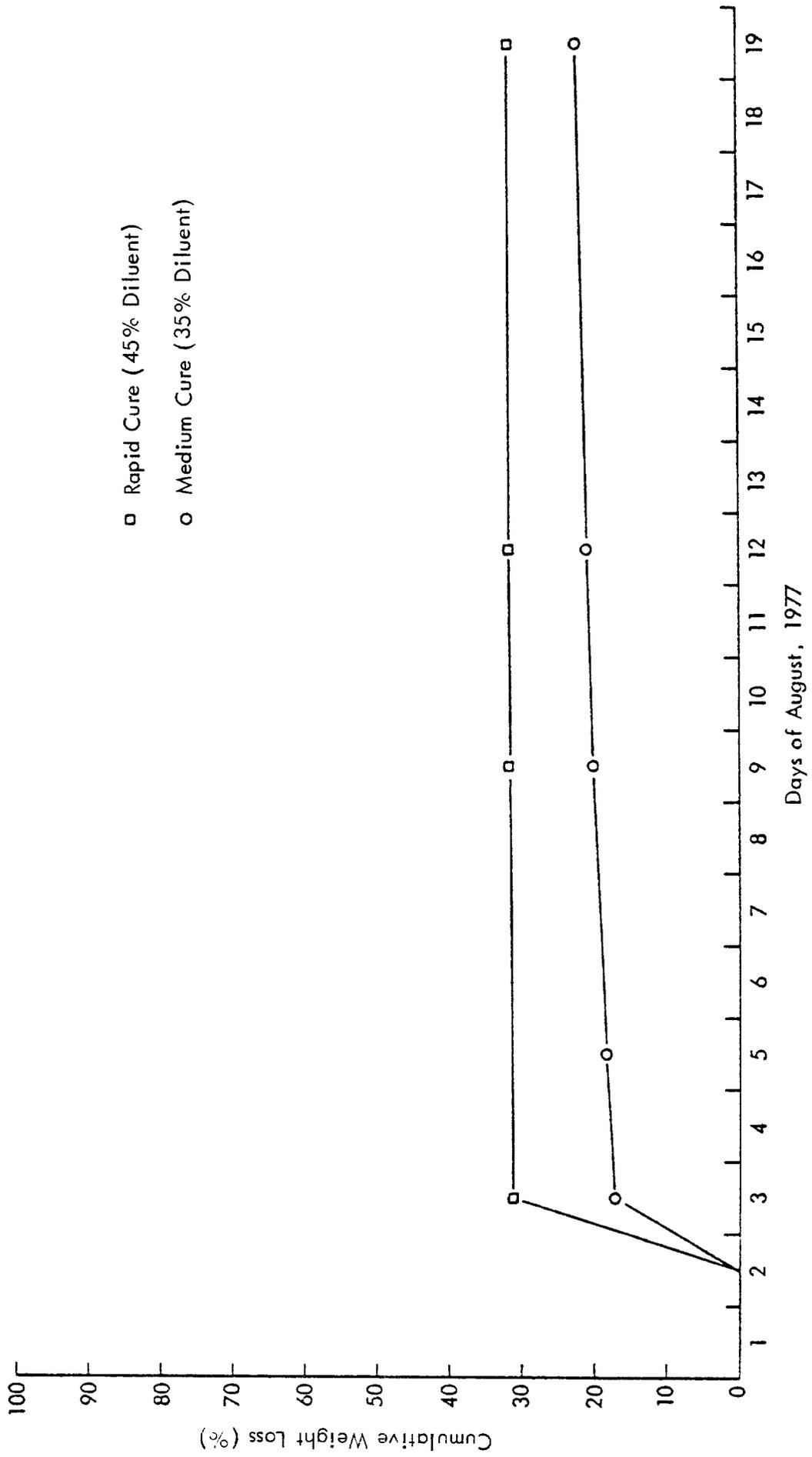


Figure 7. Weight Loss by Outback Asphalt During Curing
(Long-term GC Analysis)

TABLE 6. WEIGHT LOSS OF CUTBACK ASPHALTS RELATED TO TOTAL AND DILUENT MASS (LONG-TERM GRAVIMETRIC ANALYSIS)

Date	Rapid Cure Asphalt				Medium Cure Asphalt			
	Sample Weight (g)	Weight Loss (g)	% of Initial Weight	% of Diluent	Sample Weight (g)	Weight Loss (g)	% of Initial Weight	% of Diluent
8/ 2	2.5854	0	0	0	2.8029	0	0	0
8/ 3	1.7944	0.81	31.4	85.3	2.3413	0.47	16.8	46.3
8/ 5	-	0.82	31.8	86.4	2.3020	0.51	18.2	50.1
8/ 9	1.7760	0.82	31.8	86.4	2.2477	0.56	20.0	55.1
8/12	1.7737	0.82	31.8	86.4	2.2108	0.59	21.1	58.1
8/19	1.7706	0.82	31.8	86.4	2.1906	0.62	22.1	60.8
Limiting Values		0.95	37.0	100.0		1.01	36.0	100.0

- No data.

TABLE 7. ORGANIC EMISSIONS FROM CUTBACK ASPHALTS
(Long-term gravimetric analysis)



Day	Rapid Cure (45% Diluent)		Medium Cure (35% Diluent)	
	% of Diluent Weight Lost	Emission Rate ($\mu\text{g}/\text{min-g}$)	% of Diluent Weight Loss	Emission Rate ($\mu\text{g}/\text{min-g}$)
0	0		0	
1	75.7	3,125.4	18.5	28.
2	82.6	21.	21.6	5.6
5	85.9	3.5	45.4	14.
6	86.5	1.4	48.0	4.2
7	87.1	1.4	49.9	3.5
8	87.6	1.4	51.6	2.8
12	88.8	0.7	54.0	0.7
15	89.6	0.7	55.5	0.7
19	90.3	0.6	57.1	0.6
22	90.8	0.4	58.1	0.6
26	91.4	0.4	59.2	0.4
29	91.8	0.3	60.1	0.5
40	92.6	0.2	62.1	0.3
49	93.0	0.1	63.4	0.2
61	93.4	0.07	64.7	0.2
72	93.9	0.1	66.1	0.2
86	94.3	0.06	67.7	0.2
100	94.5	0.05	68.9	0.1
111	94.7	0.03	69.9	0.1
124	94.8	0.02	70.9	0.1

TABLE 8. EMISSIONS FROM ASPHALT CEMENT AND EMULSIFIED ASPHALT
(Long-term gravimetric analysis)

Day	Asphalt Cement		Emulsified Asphalt ^{c/}	
	% Weight Loss	Emission Rate ($\mu\text{g}/\text{min-g}$)	% Weight Loss	Emission Rate ($\mu\text{g}/\text{min-g}$)
0				
1	0	0	15.6	472
4	0	0	25.7	9.7
6	0	0	27.3	2.8
7	0	0	30.7	1.4
11	0	0	30.8	1.4
13	0	0	31.5	0.5
15	0	0	31.6	0.5
19	0	0	32.2	0.3
22	0	0	32.3	0.2
29	0	0	32.5	0.1
36	0	0	32.6	0.06
40	0.022 ^{a/}	0.4 ^{b/}	32.7	--
41	0.044	0.1	32.8	--
42	0.063	0.2	32.9	--
43	0.066	0.04	32.9	0.03
46	0.072	0.06	32.9	--
47	0.081	0.1	--	--
48	0.090	0.1	--	--
49	0.092	0.05	--	--
50	0.092	0.01	--	--
53	0.093	0	--	--
54	0.098	0.02	--	--
55	0.110	0.007	--	0.03
57	0.108	0.1	33.0	--
60	0.110	0	--	--
61	0.110	0.03	--	0.03
63	0.110	--	33.0	--
68	0.110	0	33.0	0.02

^{a/} Temperature of sample raised to 60°C.

^{b/} Per 24 hr of sunlight; sample temperature at 60°C.

^{c/} These values include water emissions.

-- No data.

The medium-cure asphalt samples lost an average of 70.9% of the initial diluent quantity in the 124 days. The emission rate had declined to an average of 0.14 $\mu\text{g}/\text{min-g}$ by the 124th day. The emission rate was still declining, but at a slower rate than the rapid-cure sample emission rates. As seen in the earlier experiments, the rapid-cure samples had greater emission rates than the medium-cure samples initially, but the rapid-cure emission rates declined faster to become far less than those of the medium-cure samples. However, the total emissions from rapid-cure asphalt still exceeded the total emissions from medium-cure asphalt.

The asphalt cement exhibited such a small emission factor at 25°C that it was not measurable over 36 days (Table 8). This indicates that the emission rate for this sample was much less than the 0.04 $\mu\text{g}/\text{min-g}$ (average value) shown in Table 3. However, the rates shown in Table 2 indicate that asphalt cement (penetration grade 85/100) emissions fall below 0.01 $\mu\text{g}/\text{min-g}$ in the 125th min of the test, or, at the time the sample was reaching temperatures of 25°C. On the 37th day, the asphalt cement samples were placed beneath a heatlamp which maintained their surface temperatures near 60°C. Over the next 28 days, 0.11% of the initial sample mass was lost. The emission rates varied greatly throughout the 28 days, ranging from 0.042 to 0.42 $\mu\text{g}/\text{min-g}$. An average value for the time period was 0.09 $\mu\text{g}/\text{min-g}$ with the sample temperature near 60°C.

Emulsified asphalt mass losses and emission rates include both organic compounds and water losses. Thirty-three percent of the initial mass was lost over the 68 days. Emission rates declined throughout the time period.

3.4 PERTURBATION ANALYSIS

On the 17th day of the long-term tests (August 1, 1977), the surfaces of the asphalt samples were disturbed by poking them with a glass rod. The emission rates before and after the perturbation are shown in Table 9. Emissions from medium-cure asphalt increased by 44%, while emissions from rapid-cure asphalt increased by 7%. The emission rates of both asphalts decreased rapidly either approaching (medium-cure) or falling below (rapid-cure) the original emission rates. Rapid-cure emissions reached the original rate within 20 min. Medium-cure emissions dropped to 9.2 $\mu\text{g}/\text{min}$ (original rate = 8.2 $\mu\text{g}/\text{min}$) in 60 min. This indicates the possibility that traffic over an asphalt surface could disturb the surfaces sufficiently to increase the emission rates for short time periods.

3.5 DILUENT LOSSES DURING PREPARATION OF CUTBACK ASPHALT

The final experiments (August 2, 1977) involved the measurement of the quantity of diluent lost during mixing of the diluent and asphalt cement in the laboratory. The data are shown in Table 10. As would be expected, the rapid-cure diluent evaporated at a higher rate (0.7%/min of the initial weight) than the medium-cure diluent (0.38%/min).

TABLE 9. SURFACE PERTURBATION EXPERIMENT--CUTBACK ASPHALTS

Time (min)	Emission rate ($\mu\text{g/g/min}$)	
	Medium cure	Rapid cure
0	3.9	-
10	3.9	-
20	3.8	-
30	3.8	1.9
40	3.8	1.8
50	3.8	1.7 } Surface
60	3.7 } Surface	1.8 } Film broken
70	5.4 } Film broken	1.8
80	5.3	1.6
90	4.9	1.5
100	4.7	1.5
110	4.4	1.5
120	4.2	-

--No data

TABLE 10. DILUENT LOST DURING PREPARATION OF CUTBACK ASPHALTS

<u>Rapid cure</u>			
Asphalt	20 ml	9.5182 g	
Diluent	16 ml	5.6090 g	200°F
R.C. asphalt	-	14.9691 g	120°F
Time of mixing		4 min	
Weight lost		0.1581 g	
Summary: 2.8% of the solvent was lost in 4 min during mixing (0.7%/min).			
<u>Medium cure</u>			
Asphalt	20 ml	9.2499 g	200°F
Diluent	11 ml	5.3507 g	120°F
M.C. asphalt	-	14.4355 g	
Time of mixing		8 min	
Weight lost		0.1651 g	
Summary: 3.1% of the solvent was lost in 8 min during mixing (0.38%/min).			
Note: Mixing was done in a 50-ml beaker.			

SECTION 4.0

EXPERIMENTS ON FIELD-OBTAINED SAMPLES OF ASPHALT PAVEMENT

Samples plugs were obtained from medium-cure cutback asphalt roadways of different ages in order to ascertain nonmethane organic emission rates from asphalt that had cured for up to 3 years. Experiments were performed to measure emissions from the road samples, emissions from the samples as the surfaces were physically disturbed, and emissions from crumpled samples after a 7-day period. In addition, the effect of temperature on emission rates was investigated. The following subsections discuss the data and results of this portion of the study.

4.1 EMISSION RATES OF UNDISTURBED SAMPLES AT 27°C and 58°C

Two series of experiments were performed on the 12 plugs obtained from four medium-cure asphalt roadways in Missouri. The first series measured emissions of nonmethane organics from samples at temperatures of 27°C (80°F). The second series measured emissions while the sample temperatures were elevated to 58°C (136°F) through the use of a heatlamp. The emissions from each sample were measured by the Beckman 6800 total hydrocarbon GC for 1-hr periods (12 concentration measurements per hour).

The results of the experiments with samples at 27°C are shown in Table 11. As shown in Figure 8, the data seem to indicate an overall decrease in emissions relative to the age of the cutback roadway surface. Sample NN₃ - 1975 had a high emission rate due to the dislodging of a piece of surface aggregate exposing relatively fresh asphalt cement.

The results of the second series of experiments, which were conducted to determine the effect of asphalt temperature on emission rates, are given in Table 12. As shown in Figure 9, the data exhibit a near linear relationship between temperature and emission rates.

4.2 EMISSION RATES OF SAMPLES DURING SURFACE PERTURBATION AT 54°C

In the next series of experiments, two asphalt plug samples were heated and rapped to note the effect that disturbing the surface area would have on emissions.

TABLE 11. ORGANIC EMISSION RATES FOR ASPHALT PAVEMENT
PLUGS AT 27°C^{a/}

Sample	Initial Weight ^{b/} (g)	Temperature (°C/°F)	TNMHC ^{a/} (ppm)	Emission Rates		
				µg/min	µg/min-m ² surface	µg/min-g asphalt pavement ^{b/}
ZZ ₁ -1977	645.0	27/80	0.19	0.16	43.2	0.0002
ZZ ₂ -1977	304.1	27/80	0.13	0.11	29.7	0.0004
ZZ ₃ -1977	750.0	27/80	0.31	0.25	67.6	0.0003
Mean-1977	--	27/80	0.21	0.17	46.8	0.0003
FF ₁ -1976	503.0	27/80	0.13	0.11	29.7	0.0004
FF ₃ -1976	479.3	27/80	0.32	0.26	70.3	0.0005
Mean-1976	--	27/80	0.23	0.19	50.0	0.0005
NN ₁ -1975	184.8	27/80	0.02	0.02	5.4	0.0001
NN ₂ -1975	335.0	27/80	0.04	0.03	8.1	0.0001
NN ₃ -1975	472.6	27/80	0.39	0.32	84.5	0.0007
Mean-1975	--	27/80	0.15	0.12	32.7	0.0003
AA ₁ -1974	426.9	27/80	0.13	0.11	29.7	0.0003
AA ₂ -1974	419.5	27/80	0.18	0.15	40.5	0.0004
AA ₃ -1974	436.9	27/80	0.14	0.11	29.7	0.0003
Mean-1974	--	27/80	0.15	0.12	33.3	0.0003
ZZ ₃ -1977	750.0	24/75	0.27	0.22	59.5	0.0003
FF ₃ -1976	479.3	24/75	0.30	0.24	64.8	0.0005
NN ₃ -1975	472.6	24/75	0.36	0.29	78.4	0.0006
ZZ ₁ -1977	645.0	27/80	4.2	3.49 ^{c/}	943.2 ^{c/}	0.0054 ^{c/}

^{a/} Total nonmethane organics.

^{b/} Includes aggregate.

^{c/} Emissions were allowed from all surfaces--top, bottom and sides.

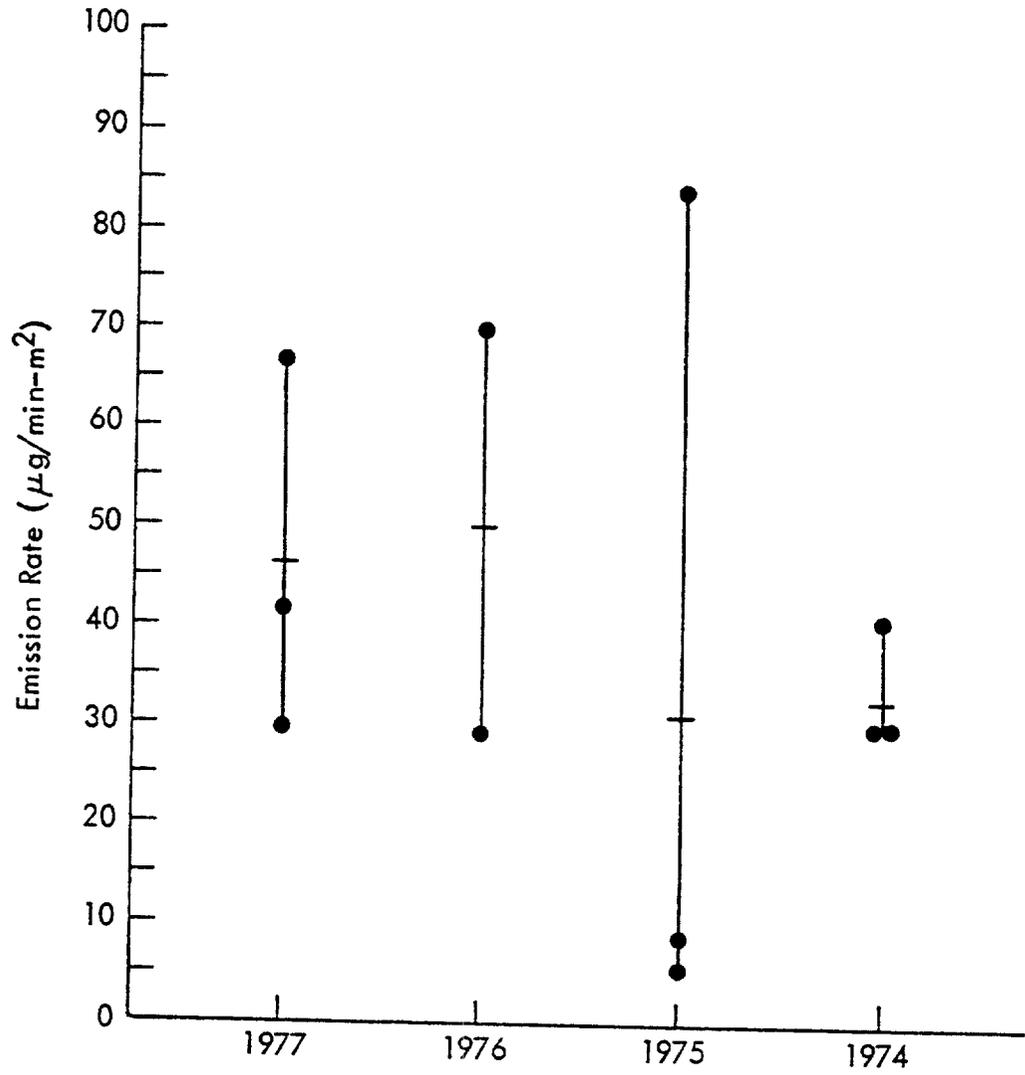


Figure 8. Range and Mean Emission Rates of Asphalt Pavement Plugs at 27°C

TABLE 12. ORGANIC EMISSION RATES FOR ASPHALT PAVEMENT PLUGS
AT ELEVATED TEMPERATURES

Sample	Initial Weight ^{b/} (g)	Temperature (°C/°F)	TNMHC ^{a/} (ppm)	Emission Rates		
				µg/min	µg/min-m ² surface	µg/min-g asphalt pavement
FF ₁ -1976	503.0	27/80	0.13	0.11	29.7	0.0004
FF ₁ -1976	503.0	39/102	0.30	0.24	64.9	0.0005
FF ₁ -1976	503.0	52/126	0.38	0.31	83.8	0.0006
FF ₁ -1976	503.0	58/136	0.54	0.44	118.9	0.0009
NN ₁ -1975	184.8	27/80	0.02	0.02	5.4	0.0001
NN ₁ -1975	184.8	56/133	0.16	0.13	35.1	0.0007
NN ₃ -1975	472.6	28/82	0.32	0.26	70.3	0.0006
NN ₃ -1975	472.6	29/84	0.50	0.41	110.8	0.0009
NN ₃ -1975	472.6	43/110	0.57	0.47	127.0	0.0010
NN ₃ -1975	472.6	51/124	0.73	0.60	162.2	0.0013
NN ₃ -1975	472.6	52/126	0.80	0.65	175.7	0.0014
NN ₃ -1975	472.6	54/130	0.86	0.70	189.2	0.0015
NN ₃ -1975	472.6	57/134	0.97	0.79	213.5	0.0017

a/ Total nonmethane organics.

b/ Includes aggregate.

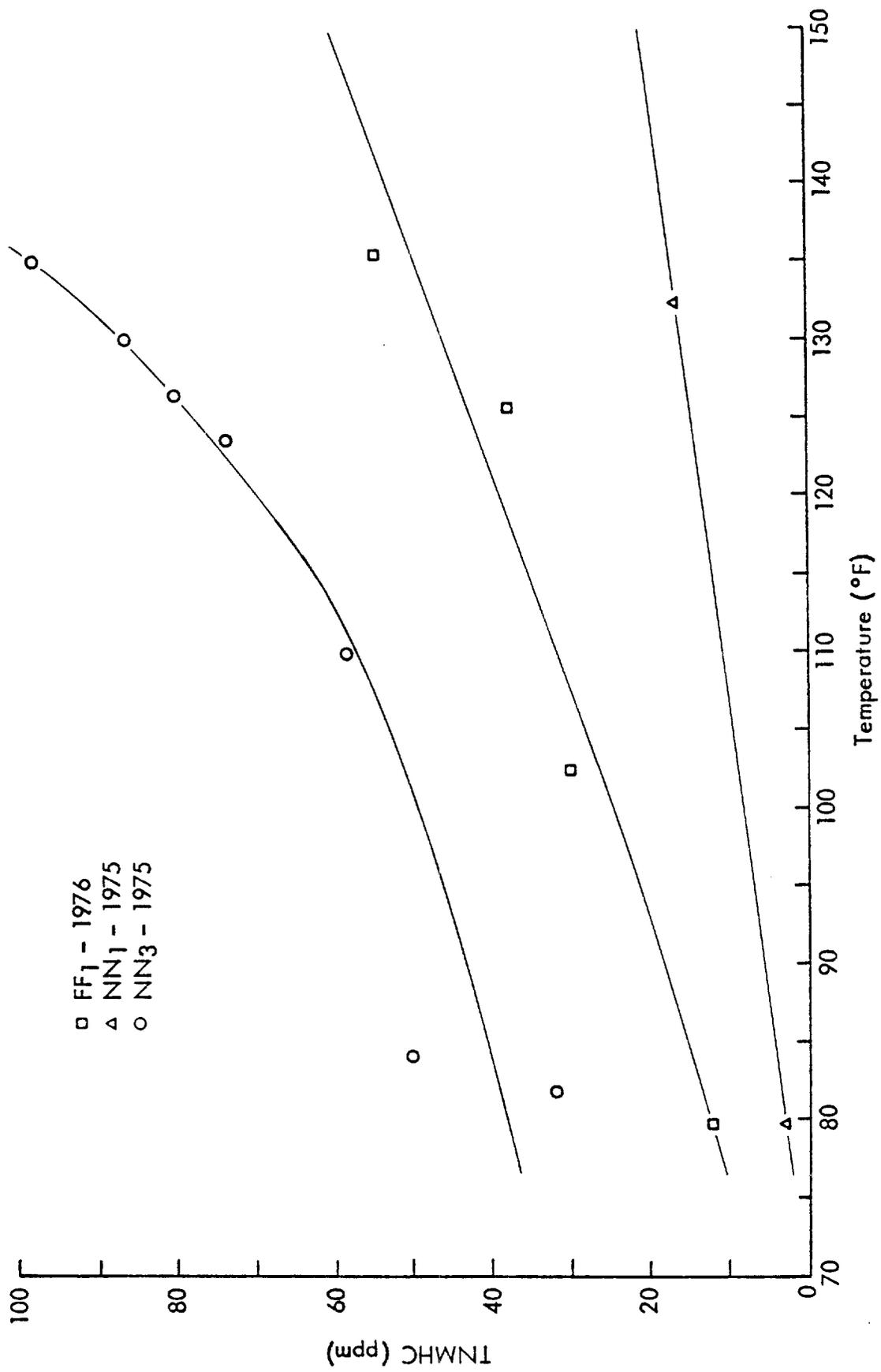


Figure 9. Temperature Dependency of Asphalt Pavement Plug Emissions

The top surface layer of each roadway plug was heated to 54°C (130°F) and rapped with a hammer to simulate the effect of vehicular travel on summer days. As noted in Table 13, one plug (FF₁ - 1976) showed no emission change while another plug (NN₃ - 1975) showed a 27% increase in emissions due to rapping. This increase may have resulted from uneven heating of the sample, the dislodging of the surface aggregate exposing relatively fresh asphalt cement, or the effect of rapping.

4.3 EMISSION RATES OF CRUMBLED SAMPLES AT 27°C

In this experiment, the top layer (upper 1/2 in.) was separated from samples representing each year (1975 through 1977). This separated layer was fractured into segments finer than 1/4 in. The emissions were monitored just after fracture and 7 days later. As shown in Table 14, the emission rates decreased by 63 to 71% during this period. However, the emission rates were still greater (by a factor of 15 to 30) than those recorded initially during the testing of room temperature samples (see Table 11). Thus, it appears that quantities of volatile organics still remain in the asphalt cement even after 2.5 years of exposure.

TABLE 13. ASPHALT PAVEMENT PLUG EMISSION RATES DURING PERTURBATION

Sample	Condition/ temperature (°C)	TNMHC (ppm)	Emission Rates			Percentage change (%)
			µg/min	µg/min-m ² surface	µg/min-g asphalt pavement ^{a/}	
FF ₁ -1976	Nonrapped/54	0.57	0.47	127	0.0009	0
FF ₁ -1976	30 raps/54	0.57	0.47	127	0.0009	
NN ₃ -1975	Nonrapped/54	0.86	0.70	189.2	0.0015	27
NN ₃ -1975	30 raps/54	1.09	0.89	240.5	0.0019	

^{a/} Includes aggregate.

TABLE 14. ASPHALT PAVEMENT PLUG EMISSION RATES AFTER FRACTURE

Sample	Weight of sample (g)	Condition/temperature (°C)	TNMHC (ppm)	$\mu\text{g}/\text{min}$	$\mu\text{g}/\text{min}\cdot\text{g}^{\text{a}}/\text{asphalt pavement}$	Percentage change (%)
ZZ ₂ -1977	124.1	Day 1/26	11.22	9.2	0.074	65
ZZ ₂ -1977	121.9	Day 7/26	3.96	3.2	0.026	
FF ₁ -1976	89.9	Day 1/26	11.73	9.6	0.11	63
FF ₁ -1976	88.5	Day 7/26	4.30	3.5	0.04	
NN ₃ -1975	127.1	Day 1/26	19.84	24.5	0.13	71
NN ₃ -1975	124.8	Day 7/26	5.85	4.8	0.04	

a/ Upper 1/2 in. portion of plug.

SECTION 5.0

CONCLUSIONS

The results of the experiments on laboratory-prepared samples yielded the following information. Organic emissions from asphalt cement and emulsified asphalt were found to be less than 0.4% of the asphalt weight (or 0.02% of the asphalt concrete used in the construction of roads and parking lots) during the initial 2-hr period after mixing. The emission rates were approximately 0.02 $\mu\text{g}/\text{min-g}$ after this period. After several months of asphalt pavement curing, organics are emitted at a rate of about 1×10^{-3} $\mu\text{g}/\text{min-g}$ aggregate mix at warm temperatures and 2.5×10^{-4} $\mu\text{g}/\text{min-g}$ aggregate mix during the night and in cooler seasons.

The cutback asphalts emit at a greater rate depending on the age of cure and ambient temperature. As much as 86% of the diluents used in rapid-cure asphalts may be lost in the first 3 days, and up to 95% of the diluents may be lost by the 124th day of curing. The emission rates begin high (5,200 $\mu\text{g}/\text{min-g}$) and drop rapidly, decreasing to 0.02 $\mu\text{g}/\text{min-g}$ after 124 days. Medium-cure asphalts lose about 50% of their diluents in the first 3 days, but continue to emit at a measurable rate for some period of time. After 124 days, 71% of the diluent may be lost and the emission rate is approximately 0.1 $\mu\text{g}/\text{min-g}$.

The results of the experiments on field-obtained pavement plugs of medium-cure asphalt indicate that nonmethane organic emissions are occurring from asphalt as old as 3 years. However, the emissions of a 3-year-old cutback asphalt road are small--on the order of 0.0003 $\mu\text{g}/\text{min-g}$ pavement (with aggregate) or 0.006 $\mu\text{g}/\text{min-g}$ asphalt (no aggregate). The decrease of emission rates from 6-month-old asphalt (1977) to 3-year-old asphalt (1974) was about a factor of 2.

The effect of the asphalt temperature on emissions was well demonstrated. The emissions during the summer months will be greater than those in the winter months. On hot days, emissions can be expected to be about triple compared to the average. In addition, a diurnal cycle of emission rates can be expected where emissions increase in the afternoon and fall off after sunset.

The effect of vehicular traffic on organic emissions is not pronounced as long as the surface is unbroken. However, when surface aggregate is displaced or surface cracks created, emissions will increase until these newly formed surfaces cure.

The last experiments reaffirmed the existence of volatile organics within the aged asphalt pavement. Emission rates greatly increased as new surface areas were created by crumbling the pavement.

In summary, the experiments on the laboratory-tested samples indicated (a) asphalt cement and emulsified asphalts emit minimal amounts of nonmethane organics; (b) cutback asphalts emit large quantities of organics in the first few days of exposure as pavement; and (c) emission rates of all the asphalt types are dependent on temperature.

Comparisons may be made between the long-term experiments on laboratory-prepared samples and the field-obtained samples from rural medium-cure asphalt roadways. At the end of 17 days, the laboratory samples had lost 60.8% of the diluent initially present, and after 124 days, the samples had lost 70.9% of the diluent and were still losing at a rate of 0.14 $\mu\text{g}/\text{min-g}$. The road samples emitted volatile organics at rates of 0.005 to 0.02 $\mu\text{g}/\text{min-g}$. These data indicate that medium-cure asphalt lose approximately 60% of the diluent in a short period of time (1 to 3 days) but continue to emit organics at minimal rates for at least 3 years.

It is interesting to note that after 3 years, the cutback asphalt pavement samples at 25°C emit nonmethane organics at a rate less than fresh asphalt cement at 60°C. However, when the cutback pavement samples were elevated to 60°C, organic emissions were approximately equal to those of the asphalt cement samples at 60°C.

The best estimates of nonmethane organic emissions from asphalt materials based on this work are shown in Table 15. A graphical representation of the emission rates of the various asphalt types for different ages is shown in Figure 10.

TABLE 15. NONMETHANE ORGANIC EMISSIONS BY ASPHALT MATERIALS

Asphalt Type	Long-Term Cumulative Loss of Organics (% of asphalt weight ^{a/})	Emission Rates ($\mu\text{g/g-min}$) ^{b/}	
		Fresh	Cured
Asphalt cement	0.4	0.04	0.02
Emulsified	0.4	0.07	0.02
Rapid cure	95	580	0.02
Medium cure	71	340	0.02

^{a/} Loss on a weight basis (without aggregate).

^{b/} Weight of nonmethane organics loss per gram of asphalt (without aggregate) per minute.

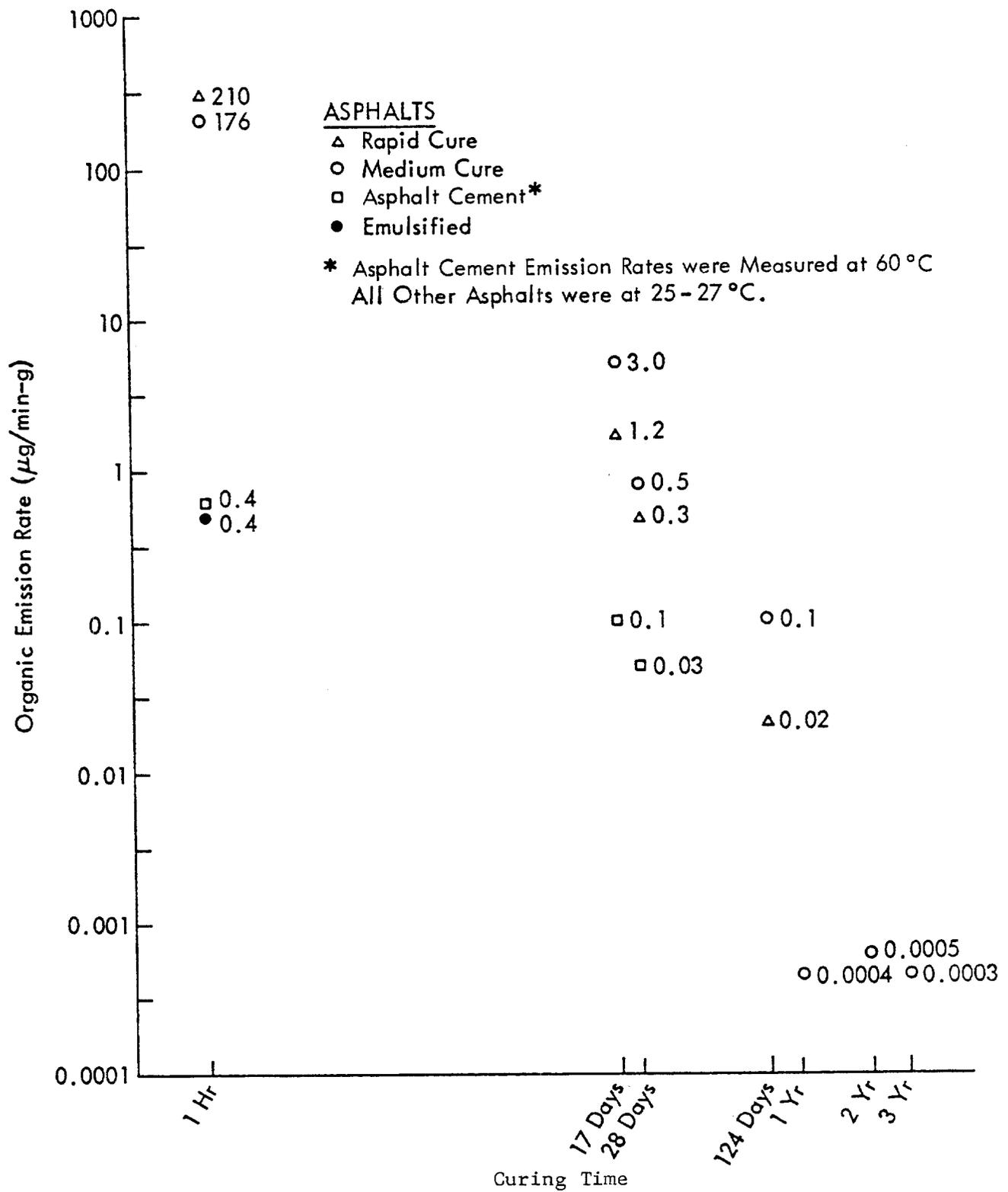


Figure 10. Organic Emission Rates of Various Asphalts

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APPENDIX A

SAMPLE CALCULATIONS FOR DETERMINING EMISSION RATE FROM GC DATA

$$\frac{(\text{Peak height} - \text{background peak height}) \times (\text{dilution}) \times 5.22 \times 0.57}{\text{peak height calibration}} = \mu\text{g}/\text{min}$$

where 5.22 = calibration concentration in ppm

0.57 = flow rate x molecular weight/molar volume
 where flow rate = 0.81 liters/min
 molecular wt = 16 g/mole
 molar volume = 22.8 liters/mole

Example

8/3/77, rapid cure asphalt, first emission rate

Peak height = 7,400
 Background peak height = 1,700
 Calibration peak height = 2,000
 Dilution = 2.8

$$\frac{(7,400-1,700)(2.8)(5.22)(0.57)}{2,000} = 23.7 \mu\text{g}/\text{min}$$

Initial sample weight = 2.5854 g

$$\text{Emission rate per gram sample} = \frac{23.7 \mu\text{g}/\text{min}}{2.5854 \text{ g}} = 9.2 \mu\text{g}/\text{min-g}$$

APPENDIX B

EXPERIMENTAL DATA FOR THERMOGRAVIMETRIC ANALYSES

TABLE B-1. ASPHALT EMISSIONS EXPERIMENTS--THERMOGRAVIMETRIC ANALYSIS
(Cumulative Weight Loss Versus Time)

Sample	Initial weight	Percent weight lost					Max. percent weight loss	Max. temp.
		Time (min)						
		20	40	60	120	180		
Asphalt cement	53.61 mg	0.07	0.09	0.12	---	---	0.13	207°C
Asphalt cement	63.49 mg	0.13	0.27	0.38	---	---	0.53	229°C
Asphalt cement	13.28 mg	0.002	0.05	0.17	0.19	0.21	0.42	200°C
Emulsified	56.41 mg	3.01	5.05	5.23	5.76	5.86	6.02	26°C
Emulsified	63.62 mg	5.60	---	---	---	---	6.80	98°C
Emulsified	57.28 mg	3.10	4.36	5.23	7.15	7.56	7.98	140°C
45% R.C. ^{a,b/}	60.87 mg	4.27	5.99	6.49	---	---	6.60	130°C
45% R.C.	51.38 mg	0.97	1.17	1.51	2.63	3.60	3.77	153°C
45% R.C.	54.27 mg	3.45	4.46	---	---	---	4.58	153°C
25% R.C. ^{c/}	56.77 mg	3.53	4.83	5.29	---	---	5.60	130°C
25% R.C.	60.54 mg	0.99	2.97	3.47	3.96	4.10	4.10	130°C
25% R.C.	57.69 mg	2.60	3.12	3.29	---	---	3.70	130°C
45% M.C. ^{d/}	57.85 mg	1.90	5.19	6.05	7.10	---	7.30	130°C
45% M.C.	54.19 mg	0.18	0.36	0.63	6.97	7.38	7.90	130°C
45% M.C.	66.04 mg	1.95	5.99	7.49	---	---	8.90	130°C
35% M.C. ^{e/}	55.29 mg	1.81	5.61	4.34	5.06	---	5.20	130°C
35% M.C.	55.33 mg	0.54	2.53	3.79	---	---	4.70	130°C
35% M.C.	57.57 mg	2.26	4.52	4.95	---	---	5.30	130°C

^{a/} All percentages for cutback asphalts represent the percent, by volume, of the diluent in the asphalt.

^{b/} 45% (by volume) diluent R.C. contains about 39% (by weight) diluent.

^{c/} 25% (by volume) diluent R.C. contains about 22% (by weight) diluent.

^{d/} 45% (by volume) diluent M.C. contains about 31% (by weight) diluent.

^{e/} 35% (by volume) diluent M.C. contains about 24% (by weight) diluent.

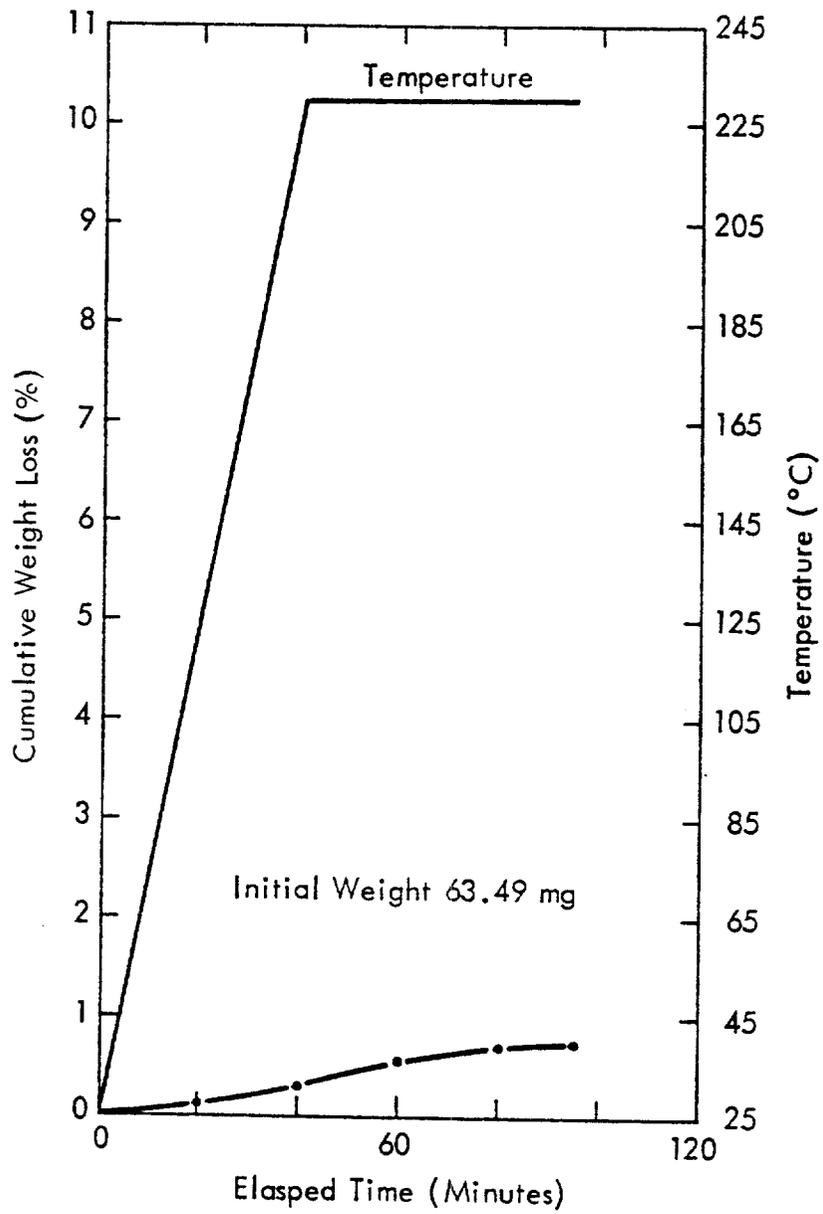


Figure B-1

Weight Loss by Penetration Grade 85/100 Asphalt Cement (Thermogravimetric Analysis)

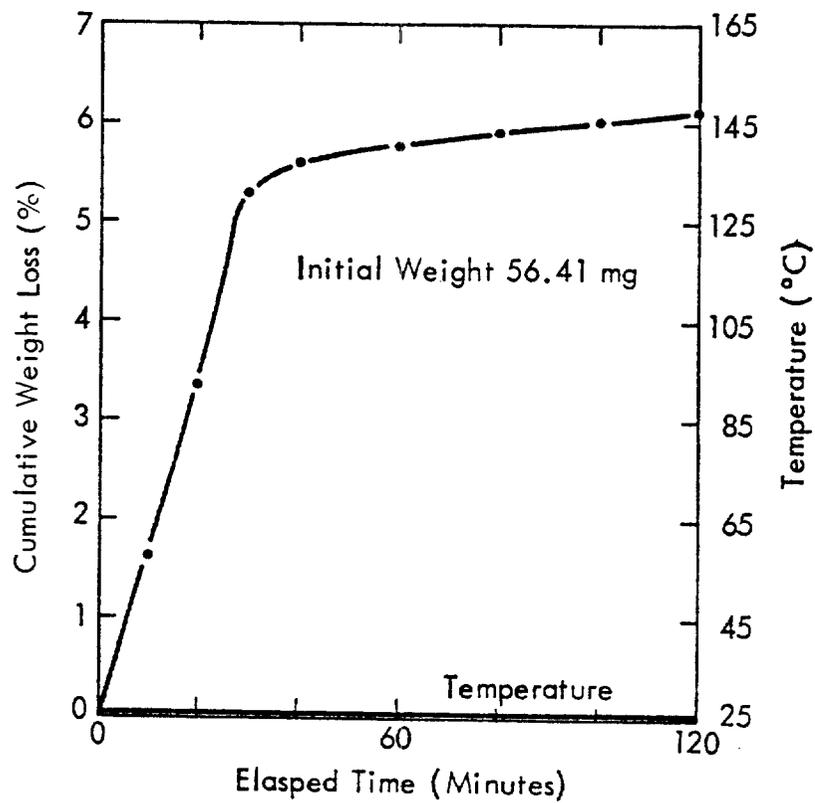


Figure B-2

Weight Loss by Emulsified Asphalt
(Thermogravimetric Analysis)

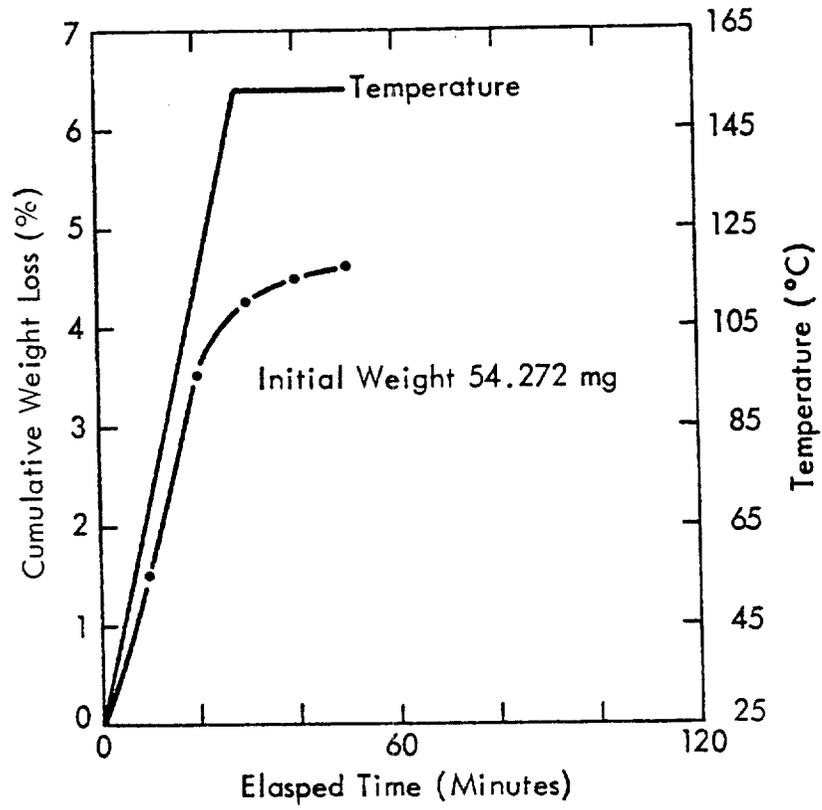


Figure B-3

Weight Loss by Rapid-Cure Asphalt (45% Diluent)
 (Thermogravimetric Analysis)

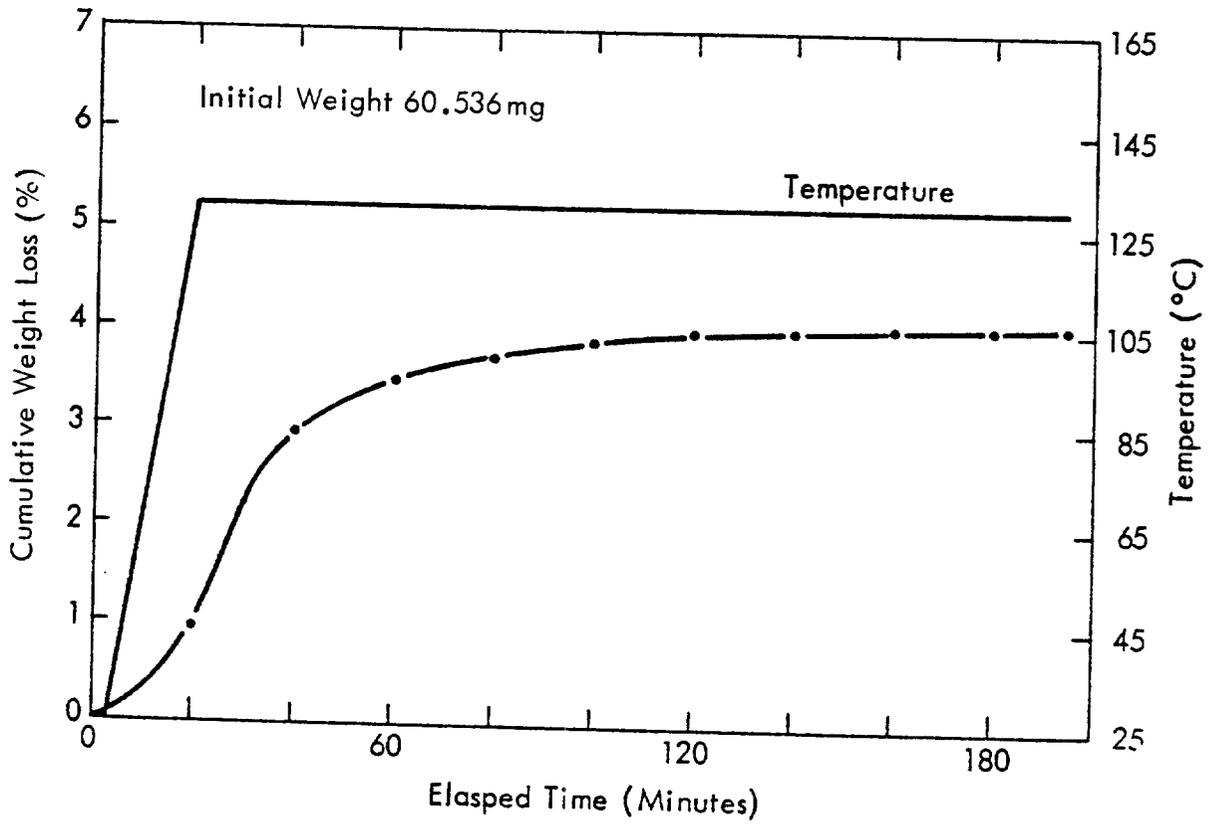


Figure B-4

Weight Loss by Rapid-Cure Asphalt (25% Diluent)
 (Thermogravimetric Analysis)

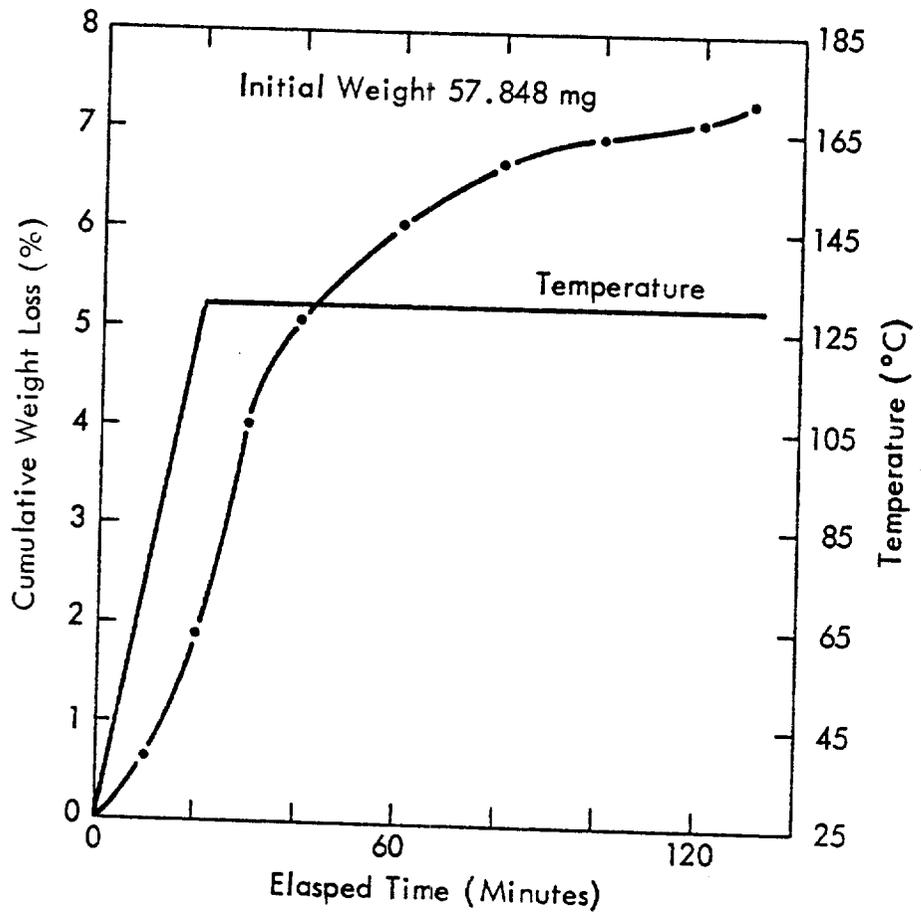


Figure B-5

Weight Loss by Medium-Cure Asphalt (45% Diluent)
 (Thermogravimetric Analysis)

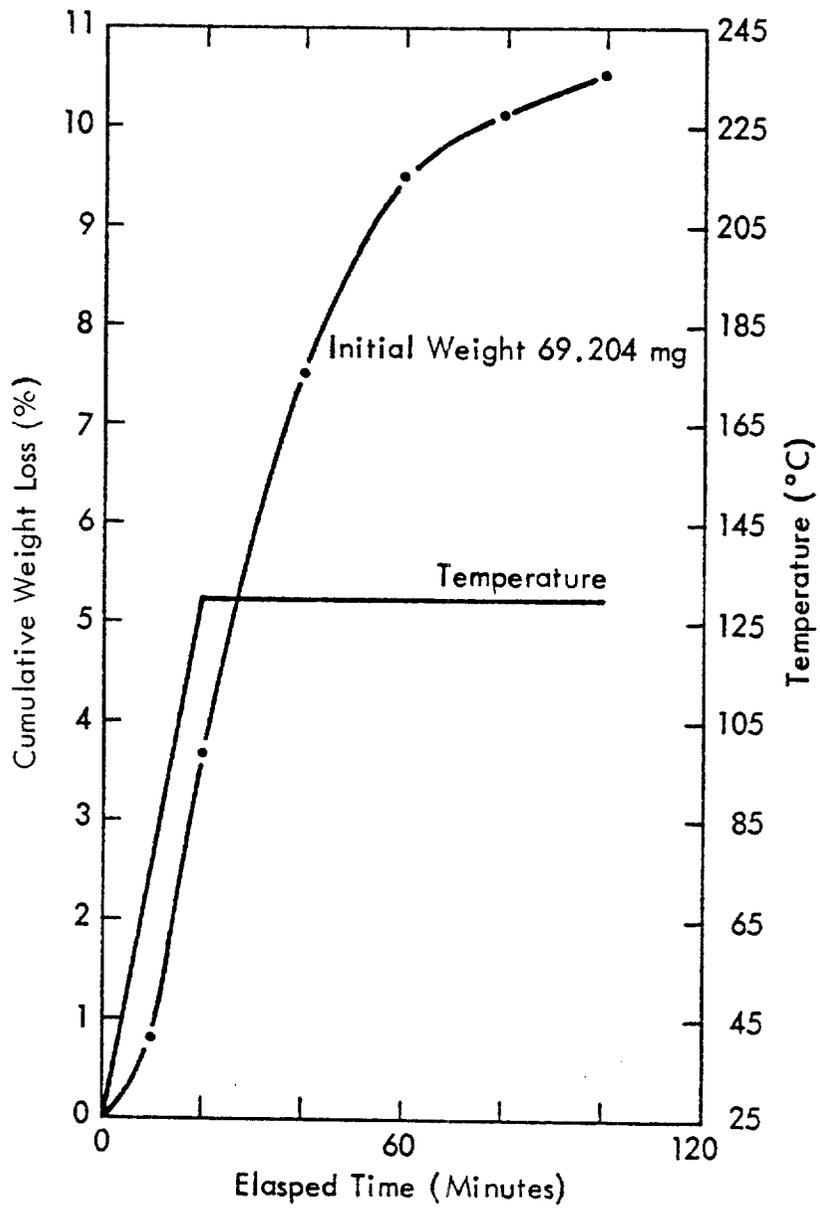


Figure B-6

Weight Loss by Medium-Cure Asphalt (35% Diluent)
 (Thermogravimetric Analysis)