REPEATABILITY OF TESTING PROCEDURES FOR RESILIENT MODULUS AND FATIGUE

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16. Abstract

Extensive use of diametral resilient modulus and fatigue testing is made by the Oregon State Highway Division to evaluate asphaltic concrete materials. Test results on similar materials (e.g., adjacent field cores), however, often indicate a poor level of repeatability.

In this study, laboratory fabricated briquettes were tested to evaluate the repeatability of the diametral modulus test at two laboratories -- Oregon State Highway Division (OSHD) and Oregon State University (OSU) — and the repeatability of the fatigue test at a single laboratory (OSU). Modulus tests at the OSHD laboratory were conducted at one temperature and three strain levels while modulus tests at the OSU laboratory were conducted at two temperatures and the same three strain levels. Fatigue testing at the OSU laboratory was conducted at two temperatures and at one initial strain level.

As a result of the test program involved in this study, the significant findings include:

1. Modulus tests are highly repeatable within each laboratory.
2. Modulus tests under similar test conditions could not be satisfactorily reproduced (at the 5% significance level) between laboratories.
3. Depending on test conditions, fatigue tests had a very low to high level of repeatability.

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ABSTRACT

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This report examines the repeatability of the diametral resilient modulus test at two laboratories — Oregon State Highway Division (OSHD) and Oregon State University (OSU) — and the repeatability of the fatigue test at a single laboratory (OSU). Modulus tests at the OSHD laboratory were conducted at one temperature and three strain levels while modulus tests at the OSU laboratory were conducted at two temperatures and the same three strain levels. Fatigue testing at the OSU laboratory was conducted at two temperatures and at one initial tensile strain level.

As a result of the test program involved in this study, the significant findings include:

1. Modulus tests are highly repeatable within each laboratory.
2. Modulus tests under similar test conditions could not be satisfactorily reproduced (at the 5% significance level) between laboratories.
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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy presented herein. The contents do not necessarily reflect the official views or policies of the Oregon Department of Transportation or the Federal Highway Administration.

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1.0 Introduction

1.1 Problem Statement

The Oregon State Highway Division (OSHD) currently makes extensive use of diametral resilient modulus and fatigue testing to evaluate the relative expected performance of asphalt concrete materials used for the wearing course on Oregon's state highways. Two recent studies, one on cold in-place recycling (CIR) and the other an on-going study of pavements constructed with various asphalt additives, have utilized the results of these tests as an integral part of the studies (1,2).

Resilient modulus and fatigue tests for the CIR study were primarily conducted at Oregon State University (OSU). In this study testing was performed on both field cores and laboratory prepared samples. Testing for the asphalt additives study was conducted at both the OSU and OSHD laboratories. In this latter study, these tests were performed exclusively on field cores. Test results, however, often indicated a poor level of repeatability between laboratory samples prepared from the same mix design (CIR study) and between adjacent field cores (both studies). This was particularly true of the additives study where significant differences between the two laboratories were often observed.

Another current study involving the investigation of polymer-modified asphalt concrete mixes will make use of the resilient modulus and fatigue tests to aid in establishing test procedures and specifications for these mixes (3). Because of the central role these mix property tests will play in this study, it is important to establish the repeatability (precision) of the diametral resilient modulus and fatigue tests.

1.2 Purpose

OSHD initiated this study to determine the repeatability of diametral resilient modulus and fatigue tests. More specifically, this study will provide answers for the following questions:

1. How repeatable (precise) within a single laboratory, measured in coefficient of variation, are tests for resilient modulus and fatigue?
2. Can the diametral resilient modulus results of the OSHD laboratory be reproduced by the OSU laboratory at the 5% significance level?

This study involved the testing of laboratory-fabricated samples to determine appropriate statistical parameters (e.g., standard deviation, coefficient of variation, etc.) of the test results when as much variability as possible was removed from the sample preparation and test procedures. Figure 1.1 shows the overall study approach.

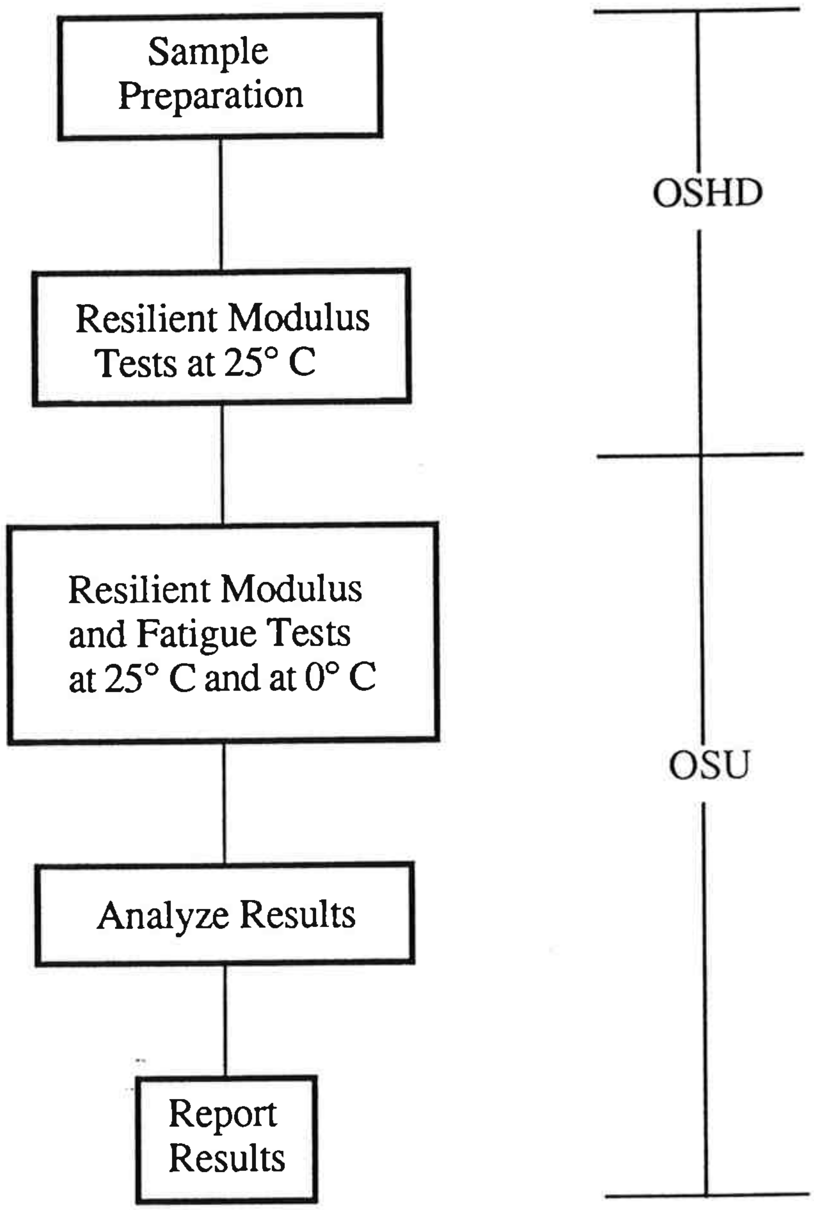


Figure 1.1 – Flowchart Showing the Scope of This Study.

2.0 Laboratory Study

2.1 Description of Laboratory Study

The laboratory study involved the fabrication and testing of two sets of samples prepared with the same mix design but having different asphalt types. The original test schedule for the laboratory study is shown in Table 2.1. A total of 48 samples were prepared by the OSHD Materials laboratory, 24 with an AC20 grade of asphalt cement and 24 with CA(P)-1 (a polymer-modified asphalt cement). Both mixes contained 1% lime. The job-mix formula, sample preparation procedure, and voids data are given in Appendix A.

After fabrication, OSHD tested 24 of the samples (12 of each asphalt type) for resilient modulus at 25°C and at three strain levels (50, 100, and 150 microstrain). All 48 samples were submitted to OSU for resilient modulus and fatigue testing. OSU conducted modulus tests using ASTM D4123 (4) and fatigue tests (Appendix B) at 25°C on the 24 samples tested by OSHD. Analysis of the modulus results for the CA(P)-1 (polymer modified) material, however, indicated a significant difference at the 5% significance level between the OSHD and OSU laboratories. The results for the AC20 samples also showed some difference between the laboratories but the difference was not found to be significant at the 5% level.

It was reasoned that the significant difference between laboratories in the modulus results for the CA(P)-1 samples may have been due to the effect of aging. That is, OSHD conducted the warm temperature (25°C) modulus tests soon after the samples were fabricated while these tests were performed at OSU several weeks later. To further investigate the possibility of aging, the 12 CA(P)-1 samples scheduled for the low temperature (0°C) tests were returned to

Table 2.1 - Original Test Schedule for the Laboratory Study.

Laboratory	Mix Type	Modulus[1]		Fatigue[2]	
		@ 25°C	@ 0°C	@ 25°C	@ 0°C
OSHD	AC20	12	-	-	-
	CA(P)-1	12	-	-	-
OSU	AC20	12	12	12	12
	CA(P)-1	12	12	12	12

[1]Tests performed at three strain levels.

[2]Tests performed at 200 microstrain (initial).

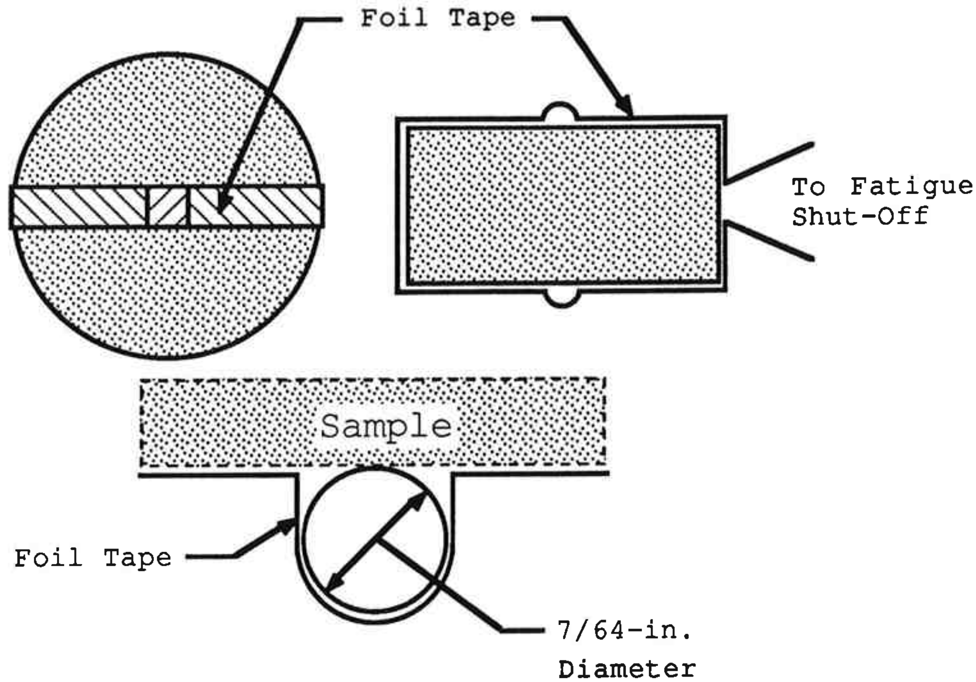
OSHD for modulus testing at 25°C and at the three strain levels of 50, 100, and 150 microstrain. Upon completion of these tests the samples were resubmitted to OSU to duplicate the tests at 25°C. To minimize any effect of aging, the modulus testing at OSU was performed the day following the modulus testing at OSHD.

Analysis of the fatigue results of tests conducted at 25°C indicated an acceptable coefficient of variation (CV ≤ 15%) for the AC20 mix but an unacceptable CV for the CA(P)-1 mix (CV ≈ 41%). This poor repeatability prompted an effort to improve the test by modifying the failure criterion. Thus, six of the cold temperature samples of each mix type were tested at the 25°C temperature using a modified failure criterion as illustrated in Figure 2.1. Permanent vertical deformation was also measured during the fatigue test. This was done to allow an alternative definition of failure as shown in Figure 2.2. The remaining six samples of each mix type were tested at the 0°C temperature using the modified failure criterion with measurement of permanent vertical deformation. Table 2.2 summarizes the revised test schedule as a result of the above changes to the original test schedule.

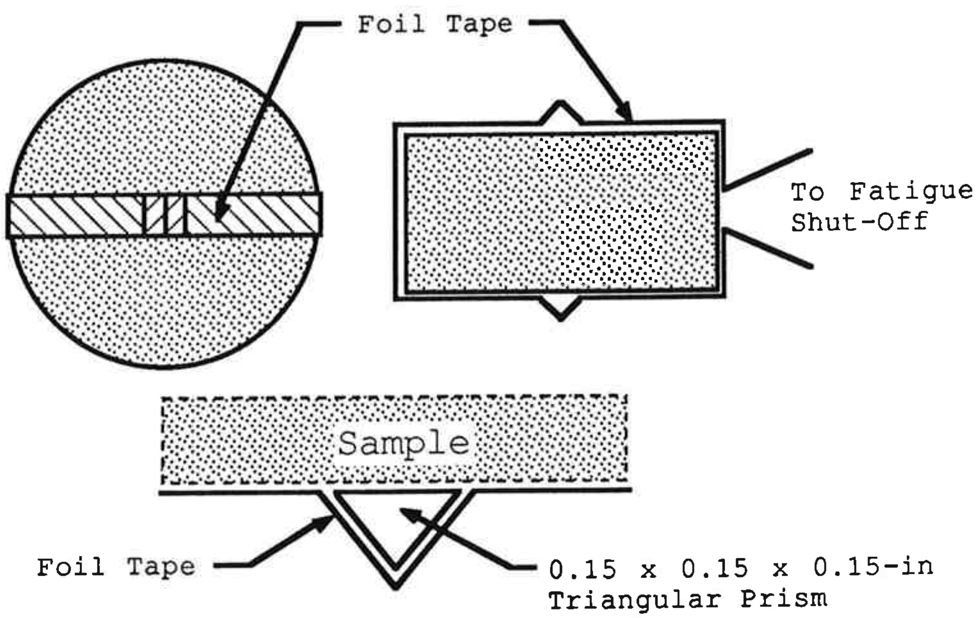
It should be noted that low temperature (0°C) modulus tests and fatigue tests (at either temperature) were not conducted by the OSHD laboratory since, at present, OSHD does not have low temperature (below ambient) or fatigue testing capabilities.

2.2 Test Equipment and Procedures

Since one of the purposes of this study was to determine the repeatability of modulus tests between laboratories, it is worthy to note the following



a) Original Failure Criterion



b) Modified Failure Criterion

Figure 2.1 – Original and Modified Failure Criteria for Fatigue.

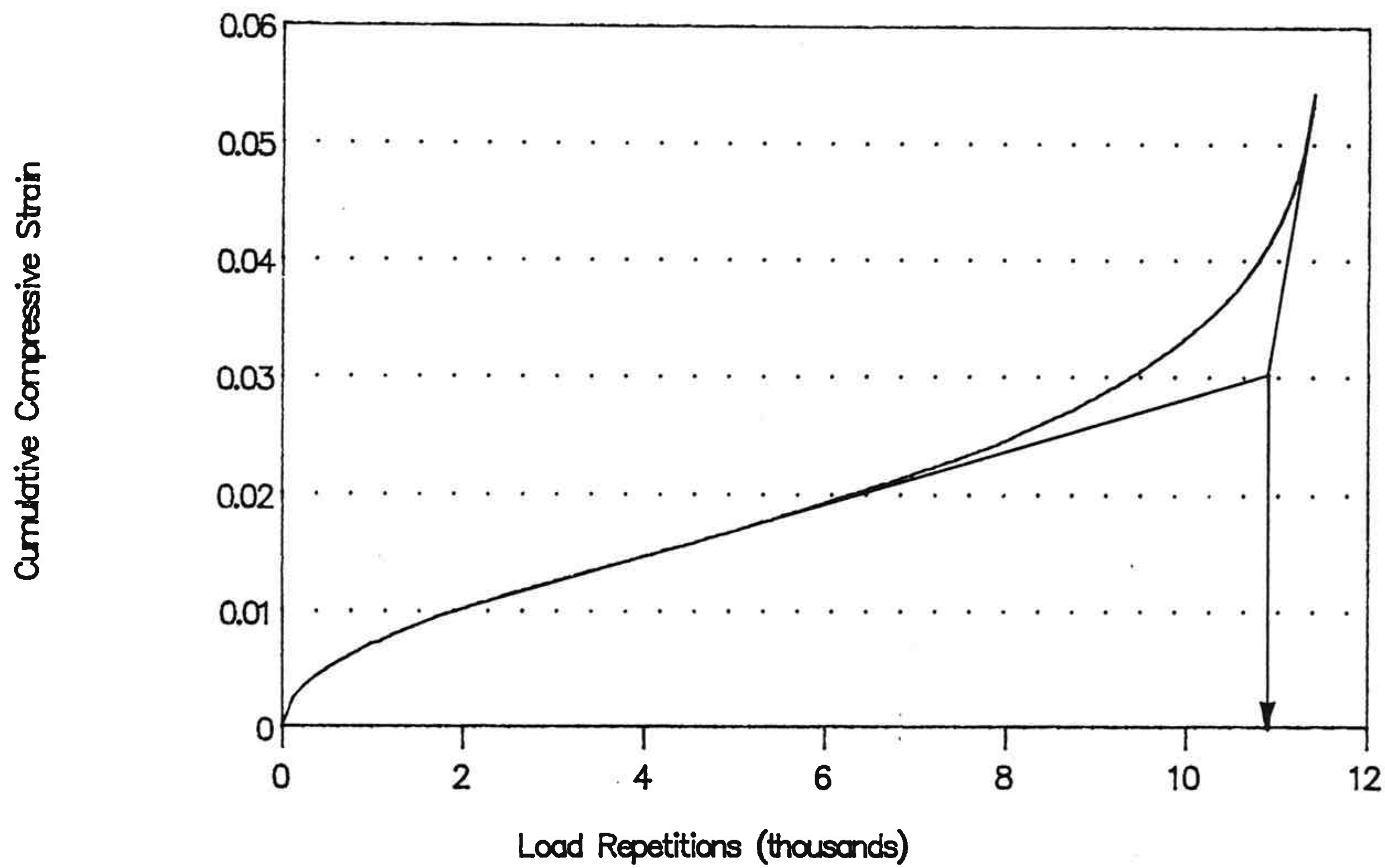


Figure 2.2 – Failure Criterion as Determined by Measurement of Permanent Deformation.

Table 2.2 - Revised Test Schedule for the Laboratory Study.

Laboratory	Mix Type	Modulus[1]		Fatigue Only[2]		Fatigue and Permanent Deformation[2]	
		@ 25°C	@ 0°C	@ 25°C	@ 0°C	@ 25°C	@ 0°C
OSHD	AC20	12	-	-	-	-	-
	CA(P)-1	24	-	-	-	-	-
OSU	AC20	18	6	12	-	6	6
	CA(P)-1	24	6	12	-	6	6

[1]Tests performed at three strain levels.

[2]Tests performed at 200 microstrain (initial).

differences in modulus test equipment and procedures between the OSHD and OSU laboratories.

Test Equipment Differences (OSU vs. OSHD). The significant differences in test equipment between the OSHD and OSU laboratories include the following:

1. The OSHD test system records changes in load and horizontal deformation via analog signal and a microprocessor while the OSU test system records these changes via analog signal and a strip chart recorder.
2. The OSHD test system applies a load pulse of variable magnitude for a duration of 0.25 second while the OSU test system applies a load pulse which closely approximates a square wave having a 0.1 second duration.
3. While both test systems can test 4-in. diameter samples, the OSHD test system utilizes load strip widths of 3/4 and 1-in. while the OSU test system uses two 1/2-in. load strips. ASTM D4123 specifies the use of a 1/2-in. load strip when testing 4-in. diameter samples (4).

Test Procedure Differences (OSU vs. OSHD). The significant differences in resilient modulus test procedures between the OSHD and OSU laboratories include the following:

1. The OSU test procedure accounts for early plastic flow (through conditioning) while this plastic flow is not accounted for in the OSHD test procedure (no conditioning).
2. The test specimen is removed from a constant temperature environment and tested in an environment which may have a different temperature in the OSHD test procedure while the test

specimen remains in the same environment in the OSU test procedure.

These differences are mentioned since variability in test results between laboratories may be influenced by differences in test equipment and procedures. Due to this possibility, further discussion of each of these differences is warranted as follows.

Recording System. The OSU test system records load and deformation via analog signal and a strip chart recorder which allows direct monitoring of the response of test specimens under loading. The OSHD test system records load and deformation via analog signal and a microprocessor which does not allow direct monitoring of the test specimen response (e.g., the shape of the load pulse and deformation trace cannot be monitored). This becomes very important when the test specimen is not responding appropriately which can significantly influence its modulus value. For example, slight ringing or shimmying of the test equipment can produce an inappropriate deformation waveform resulting in an incorrect modulus value. Such ringing cannot be directly monitored with the OSHD test system. Having a strip chart recorder, therefore, allows a manual check of the results.

Test Systems. Three test systems were employed in this study to apply repeated loads to the test specimens during modulus and fatigue testing. The OSHD test system (used exclusively for modulus testing) is an electro-pneumatic device that delivers a load pulse of variable magnitude for a duration of 0.25 seconds. That is, the load is continuously increased until the desired amount of horizontal deformation is induced in the test specimen at which time the load remains constant until the 0.25 second load duration has elapsed.

The resultant load and deformation waveforms have the appearance similar to that of a saw tooth. A rest period of 3 seconds occurs between load pulses.

OSU, on the other hand, employed two test systems both of which are different from the OSHD test system. For the warm temperature (25°C) tests, OSU employed an electro-pneumatic device that delivers a load pulse which closely approximates a square wave having a duration of 0.1 seconds. That is, the magnitude of the load pulse remains essentially constant for the 0.1 second duration of time. The time between load pulses is adjustable to accommodate a variety of rest periods. The second test system employed by OSU was an electro-hydraulic device. This test system was employed for the cold temperature (0°C) modulus and fatigue tests due to the high loads (>2500 lbs.) required to induce the desired amount of horizontal deformation. The load waveform produced by this device was that of a haversine having a frequency of 1 Hertz. By using the haversine load pulse, the test specimen continuously experienced a compressive load of variable magnitude without a rest period.

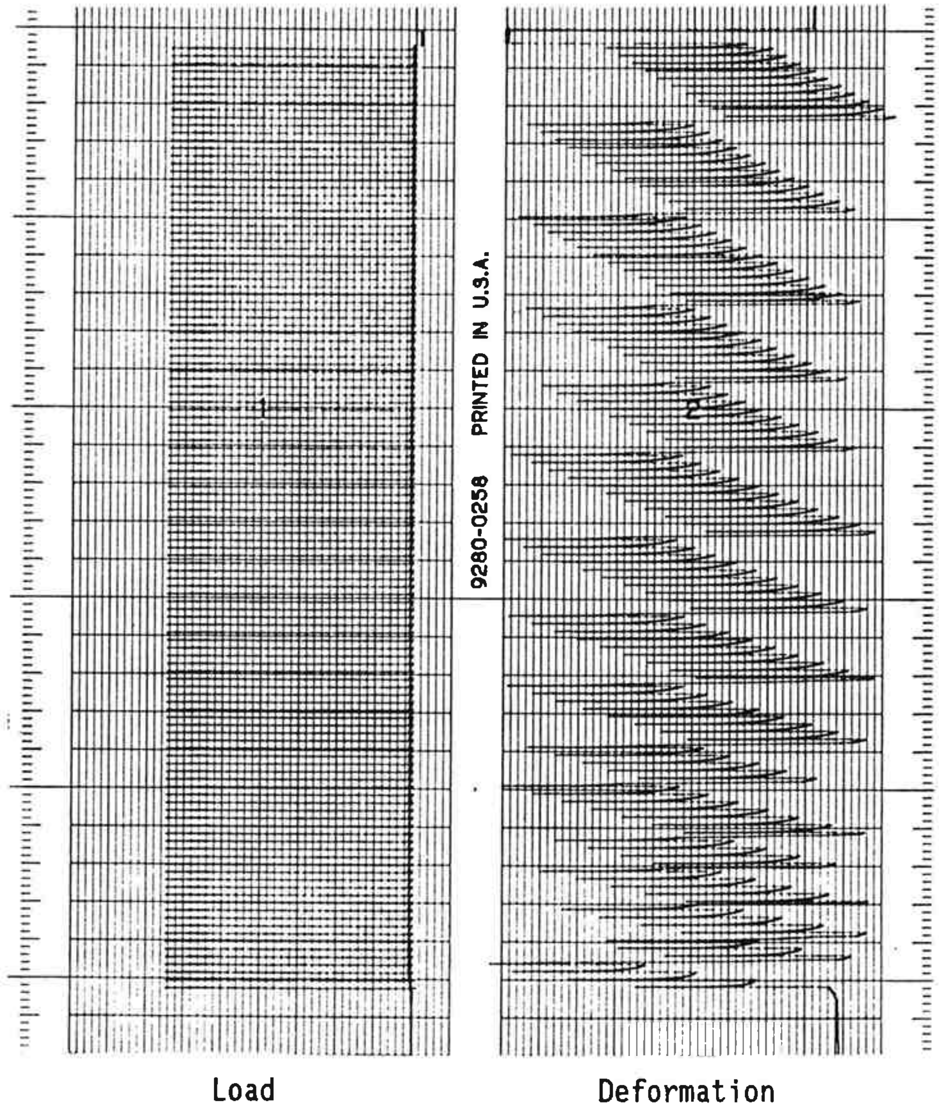
Load Strip Widths. The OSHD test system uses two load strips having different widths (3/4 and 1-in.) while the OSU test system uses two load strips having the same width (1/2-in.). The load strip width has a direct effect on the specimen modulus since different widths produce different stress profiles in the test specimen. This is particularly true of the regions in the specimen very near the load strips.

Test Specimen Conditioning. Observations of the load and deformation waveforms of specimens being tested in repeated load indirect tension (resilient modulus) indicate that the modulus increases with increasing load repetition up to between 50 and 100 repetitions. The modulus then becomes essentially constant until the specimen nears failure at which time the modulus decreases appreciably. This initial increase in modulus can be evidenced when a specimen is tested under a repeated load of constant magnitude as shown in Figure 2.3. Note that the tensile strain decreases with increasing number of repetitions resulting in the indicated increase in modulus.

This initial increase in modulus (due to early plastic flow) is not accounted for in the OSHD test procedure. That is, in the OSHD test procedure the average of the first ten load repetitions and corresponding deformations is used to determine the test specimen modulus. In the OSU test procedure, however, the test specimen is conditioned under repeated load for 50–100 repetitions before the modulus is measured, thus accounting for initial plastic flow.

<u>Test Specimen Temperature</u>. Due to the temperature susceptibility of asphalt cement and, thus, asphalt concrete mixes, it is important to maintain constant temperature environments while testing these materials. Under the OSHD test procedure, the test specimen is removed from a constant temperature airbath and tested in the ambient temperature of the laboratory (which can be several degrees Centigrade different from the airbath temperature). Under the OSU test procedure, the test specimen remains in the constant temperature airbath (±0.5 °C) throughout the test. This is not entirely true of the OSU low temperature (0°C) tests since the environmental cabinet varied in temperature between –4 and 1°C.

While there is clearly a need to improve the temperature control at the OSHD laboratory, the lack of an environmental cabinet does not explain the constant difference between laboratories in resilient modulus results (OSU consistently obtained higher modulus values). It would be expected that OSHD



Load Application Number	Load (lb)	Horizontal Deformation (μ-in.)	Resilient Modulus (ksi)
1	323	482	166
10	323	465	172
20	323	449	178
30	323	437	183
40	323	441	181
50	323	437	183
60	323	433	184
70	323	433	184
80	323	429	186
90	323	429	186
100	323	425	188

Figure 2.3 – Typical Strip Chart for the Diametral Resilient Modulus of an Asphalt Concrete Specimen.

would have consistently higher values since the samples are removed from an air bath and tested while the sample is cooling down.

2.3 Test Results

The results of resilient modulus tests conducted at 25°C* by OSHD are summarized in Tables 2.3 and 2.4. Table 2.3 summarizes the results of tests performed on the 24 samples originally scheduled to be tested at the 25°C temperature. Table 2.4 summarizes the results of tests on the cold temperature CA(P)-1 samples which were tested at the 25°C temperature.

The results of resilient modulus and fatigue tests conducted at 25°C by OSU are summarized in Tables 2.5 through 2.7. Table 2.5 summarizes the results of tests performed on the 24 samples originally scheduled to be tested at 25°C. Table 2.6 summarizes the results of tests on the cold temperature CA(P)-1 samples tested at the 25°C temperature. Note that only six of these samples were tested for fatigue and permanent deformation (using the modified failure criterion). The remaining six samples were tested at the 0°C temperature.

The results of tests conducted on six of the cold temperature AC20 samples tested at the 25°C temperature are summarized in Table 2.7. Note that these samples were tested for modulus at a dynamic loading frequency of 1 Hertz, a dynamic load duration of 0.1 sec, and at strain levels of 50, 100, and 150 microstrain. In addition, these samples were tested for fatigue using the modified failure criterion with measurement of permanent vertical deformation during the fatigue test.

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*The actual test temperature varied between 20 and 25°C.

Table 2.3 – Summary of OSHD Modulus Test Results for the Warm Temperature (25°C) Samples.

Mix Type	Sample ID	Average Height (in.)	Resilient Modulus* (ksi) @ 25°C and at		
			50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$
AC20	1	2.477	333.79	293.24	240.42
	2	2.496	376.85	263.23	266.69
Voids:	3	2.522	386.22	274.49	266.22
2.7 –	4	2.461	282.22	262.84	271.79
3.5 %	5	2.509	357.08	275.01	301.50
	6	2.513	346.28	341.34	324.12
	7	2.496	281.15	290.79	259.17
	8	2.494	272.24	249.97	248.37
	9	2.505	294.87	253.68	314.24
	10	2.473	318.99	284.57	264.90
	11	2.514	301.45	274.28	256.90
	12	2.480	389.69	333.41	311.12
		Mean:	328.40	283.07	277.12
		Std. Dev.:	42.72	28.72	28.04
		CV (%):	13.00	10.14	10.12
CA(P)-1	21	2.483	276.30	258.53	235.90
	22	2.486	269.61	235.20	207.88
Voids:	23	2.476	302.48	267.87	295.84
2.1 –	24	2.495	289.75	244.89	216.50
3.6 %	25	2.481	205.82	200.32	200.36
	26	2.471	221.07	221.57	229.39
	27	2.467	194.47	203.93	216.63
	28	2.485	207.94	204.32	239.62
	29	2.460	244.26	257.70	210.03
	30	2.519	245.61	226.15	213.40
	31	2.477	247.04	212.54	219.17
	32	2.477	246.74	217.96	228.46
		Mean:	245.92	229.25	226.10
		Std. Dev.:	34.28	23.38	24.87
		CV (%):	13.94	10.20	11.00

* Tests conducted at a dynamic loading frequnecy of 1/3 Hertz, at a dynamic load duration of 0.25 sec, and at the indicated strain level.

Table 2.4 – Summary of OSHD Modulus Test Results for the Cold Temperature CA(P)-1 Samples Which Were Tested at 25°C.

Sample ID	Average Height (in.)	Resilient Modulus* (ksi) @ 25°C and at		
		50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$
13	2.46	267.34	239.33	233.28
14	2.49	257.26	243.62	233.46
15	2.47	299.51	250.48	241.65
16	2.48	275.24	263.14	206.10
33	2.46	273.14	276.44	284.44
34	2.49	256.47	243.40	212.51
35	2.46	242.90	230.50	237.55
36	2.49	259.68	253.23	223.89
37	2.47	244.86	238.48	189.76
38	2.47	237.78	222.02	214.95
39	2.47	273.68	245.90	246.84
40	2.47	271.28	254.05	236.20
	Mean:	263.26	244.46	230.05
	Std. Dev.:	17.17	13.68	23.86
	CV (%):	6.52	5.60	10.37

* Tests conducted at a dynamic loading frequency of 1/3 Hertz, at a dynamic load duration of 0.25 sec, and at the indicated tensile strain.

Table 2.5 - Summary of OSU Modulus and Fatigue Tests for the Warm Temperature (25°C) Samples.

Mix Type	Sample ID	Average Height (in.)	Resilient Modulus* (ksi) at 25°C and @			Fatigue Life** at 25°C & 200 $\mu\epsilon$
			50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$	
AC20	1	2.477	304.13	279.32	254.36	***
	2	2.496	312.13	310.17	268.10	2128
Voids:	3	2.522	311.91	285.82	268.72	2867
2.7 -	4	2.461	343.64	285.13	258.36	2875
3.5 %	5	2.509	314.80	297.21	267.66	2718
	6	2.513	304.32	286.08	254.91	2386
	7	2.496	281.84	243.82	231.00	2775
	8	2.494	281.62	268.49	240.83	2506
	9	2.505	279.56	283.01	246.02	2442
	10	2.473	321.11	294.50	275.30	2392
	11	2.514	303.43	282.56	249.77	1717
	12	2.480	370.32	337.57	292.10	2314
		Mean:	310.74	287.81	267.26	2465
		Std. Dev.:	26.20	22.47	35.59	346
		CV (%):	8.43	7.81	13.30	14.04
CA(P)-1	21	2.483	317.16	268.53	268.37	9009
	22	2.486	311.73	273.74	273.73	3521
Voids:	23	2.476	334.59	264.62	266.47	19801
2.1 -	24	2.495	298.55	267.26	257.67	8572
3.6 %	25	2.481	266.68	232.65	231.79	10036
	26	2.471	291.94	248.78	241.68	8618
	27	2.467	272.30	230.76	225.85	11268
	28	2.485	281.26	237.34	230.97	7097
	29	2.460	295.84	263.60	247.09	10521
	30	2.519	310.61	269.24	259.24	6300
	31	2.477	300.74	261.15	256.98	9152
	32	2.477	311.13	275.90	261.86	9400
		Mean:	299.38	257.80	251.81	9441
		Std. Dev.:	19.48	16.16	16.01	3865
		CV (%):	6.51	6.27	6.36	40.94

* Tests conducted at a dynamic loading frequency of 1/3 Hertz, at a dynamic load duration of 0.1 sec, and at the indicated strain level.

** Tests conducted at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 0.1 sec, and at the indicated initial strain level.

*** No test results.

Table 2.6 – Summary of OSU Modulus and Fatigue Tests Results for the Cold Temperature CA(P)-1 Samples Which Were Tested at 25°C.

Mix Type	Sample ID	Average Height (in.)	Resilient Modulus*(ksi) at 25°C and at			Fatigue Life** at 25°C and 200 $\mu\epsilon$	
			50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$	Foil Tape	Perm Def
CA(P)-1	13	2.46	375.81	302.40	275.84	***	***
Voids: 2.1 – 3.6 %	14	2.49	312.51	285.30	258.86	***	***
	15	2.47	354.02	335.46	292.79	5549	5062
	16	2.48	320.39	276.76	254.05	5109	4836
	33	2.46	354.17	322.99	292.24	***	***
	34	2.49	343.76	290.80	261.46	4202	3753
	36	2.49	357.60	309.12	281.16	3158	2830
	37	2.47	296.37	286.48	264.52	***	***
	38	2.47	272.43	261.87	247.47	***	***
	39	2.47	326.58	307.74	283.73	4921	4627
	40	2.47	339.42	299.15	292.35	4281	4013
	Mean:		331.38	297.14	273.03	4537	4187
	Std. Dev.		28.88	20.16	15.79	846	830
	CV (%)		8.71	6.78	5.78	18.6	19.8

* Tests conducted at a dynamic loading frequency of 1/3 Hertz, at a dynamic load duration of 0.1 sec, and at the indicated strain level.

** Tested using the modified failure criteria at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 0.1, and at the indicated initial strain level.

*** Tested at 0°C.

Table 2.7 - Summary of OSU Modulus and Fatigue Tests Results for the Cold Temperature AC20 Samples Which Were Tested at 25°C.

Mix Type	Sample ID	Average Height (in.)	Resilient Modulus*(ksi) at 25°C and at			Fatigue Life** at 25°C and 200 $\mu\epsilon$	
			50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$	Foil Tape	Perm Def
AC20	1x	2.479	362.00	317.58	283.96	3307	2965
Voids: 2.7 - 3.5 %	2x	2.466	364.86	322.75	322.75	3011	2773
	3x	2.470	353.02	319.54	286.79	2062	1772
	6x	2.480	352.74	306.26	285.92	2008	1796
	8x	2.500	391.50	356.38	332.59	2603	2186
	9x	2.481	388.04	339.28	329.28	2979	2786
	Mean:		368.69	326.96	303.22	2662	2380
	Std. Dev.		17.05	17.92	22.31	535	531
	CV (%)		4.62	5.48	7.36	20.09	22.31

* Tests conducted at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 0.1 sec, and at the indicated strain level.

** Tested using the modified failure criteria and at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 0.1 sec, and at the indicated initial strain level.

The results of tests conducted at 0°C for both mix types are summarized in Table 2.8. The modulus tests were performed at a dynamic loading frequency of 1 Hertz using a haversine and at strain levels of 50, 100, and 150 microstrain. Fatigue tests were performed using the modified failure criterion with measurement of permanent vertical deformation during the fatigue test. It should be noted that failure as defined by measurement of permanent deformation was not possible for these samples. This was because of the highly erratic deformation curves.

2.4 Analysis of Results

The test results were statistically analyzed to determine the repeatability of modulus and fatigue tests within a single laboratory and to determine whether or not modulus tests are repeatable between two different laboratories. To determine repeatability of modulus test results between laboratories, a pairwise Student's t-test was performed at a 5% significance level. That is, the statistical analysis was performed on modulus test results of the same samples tested at both laboratories under approximately the same test conditions.

The results of the paired Student's t-test are summarized in Table 2.9. As indicated, there does not exist a significant difference at the 5% significance level between laboratories for only two test conditions; the AC20 mix type at the strain levels of 50 and 100 microstrain. The test results for the AC20 mix at the 150 microstrain level are just barely significantly different between laboratories. That is, the results would not be considered significantly different at the 4% level (P-value ≈ 0.04). All results are significantly different between laboratories for the CA(P)-1 mix type under

Table 2.8 - Summary of OSU Test Results for Both Mix Types at 0°C.

Mix Type	Sample ID	Average Height (in.)	Resilient Modulus*(ksi) at 0°C			Fatigue** at 0°C and 200 $\mu\epsilon$
			50 $\mu\epsilon$	100 $\mu\epsilon$	150 $\mu\epsilon$	Foil Tape
AC20 Voids: 2.7 - 3.5 %	4	2.48	2283.45	2234.28	2112.60	810
	5	2.48	2118.53	1880.18	1855.37	1770
	7	2.48	2408.18	2304.60	2196.20	3211
	10	2.49	1614.17	1621.60	1639.66	1581
	11	2.46	1934.11	1875.31	1866.97	***
	12	2.49	1707.77	1789.86	1697.26	8320
	Mean:		2011.04	1950.97	1894.68	3138.40
	Std. Dev.		315.87	264.76	221.24	3023.81
	CV (%)		15.7	13.6	11.7	96.4
CA(P)-1 Voids: 2.1 - 3.6 %	13	2.46	2122.56	2147.99	2055.28	19534
	14	2.49	1689.95	1684.95	1697.26	9222
	33	2.46	2097.44	2019.99	1900.16	3888
	35	2.46	1680.88	1677.92	1752.66	7411
	37	2.47	1800.47	1918.22	1893.44	***
	38	2.47	1711.48	1866.20	1882.65	1254
	Mean:		1850.46	1885.88	1863.58	8261.80
	Std. Dev.:		205.61	185.33	125.94	7016.90
	CV (%):		11.1	9.8	6.8	84.9

* Tests conducted at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 1 sec, and at the indicated strain level.

** Tested using the modified failure criteria and at a dynamic loading frequency of 1 Hertz, at a dynamic load duration of 1 sec (variable magnitude), and at the indicated initial strain level.

*** No test results.

Table 2.9 - Summary of Statistical Analysis (Student's t-test) of Modulus Test Results at 25°C Between Laboratories.

Mix Type	Strain Level ($\mu\epsilon$)	Mean*	Standard Deviation	t crit. (5%)	t calc.	Sig. Diff. ?	P-value
AC20	50	17.6675	36.7675	±2.20	1.665	No	0.2 > P > 0.1
Voids: 2.7 - 3.5 %	100	-4.7358	29.9903	±2.20	-0.547	No	P < 0.2
	150	18.1925	27.5872	±2.20	2.284	Yes	P ~ 0.05
CA(P)-1	50	-53.4533	19.8634	±2.20	-9.322	Yes	P < 0.001
Voids: 2.1 - 3.6 %	100	-28.5492	17.8961	±2.20	-5.526	Yes	P < 0.001
	150	-25.7100	25.2222	±2.20	-3.449	Yes	0.01 > P > 0.002
CA(P)-1**	50	-68.1233	22.7912	±2.20	-10.354	Yes	P < 0.001
Voids: 2.1 - 3.6 %	100	-52.6725	12.9436	±2.20	-14.097	Yes	P < 0.001
	150	-42.9775	17.2747	±2.20	-8.618	Yes	P < 0.001

* Mean represents the average difference between OSHD and OSU modulus test results (i.e., $M_{R(OSHD)} - M_{R(OSU)}$).

** Cold temperature samples tested at the 25°C temperature.

all test conditions. In fact, all results are significantly different at the 1% level (all P-values are less than 0.01) for the CA(P)-1 mix type.

To determine the precision (or repeatability) of modulus test results within a single laboratory, the coefficient of variation** was determined for each set of test results. These results are summarized in Table 2.10. As indicated, the coefficients of variation range between 4.6 and 13.3% for the OSU test results at 25°C while those for OSHD range between 5.6 and 13.9% at the same temperature. The coefficients of variation range between 6.8 and 15.7% for the cold temperature test results.

The repeatability of fatigue test results were also measured in terms of the coefficient of variation. These results are summarized in Table 2.11. As indicated, the coefficients of variation are reasonable for both mix types tested at 25°C when either the modified or the permanent deformation failure criteria are used. At the same temperature, using the initial failure criterion method, the coefficient of variation for the AC20 mix is reasonable but that for the CA(P)-1 mix is poor. At the 0°C temperature, the coefficient of variation is very poor for both mix types which were tested using the modified failure criterion.

2.5 Discussion of Results

Resilient Modulus Testing. The results of modulus tests on the same specimens between laboratories were determined to be significantly different for the CA(P)-1 (polymer-modified) mix while those for the AC20 mix were, for

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**CV = coefficient of variation

= (Std. Dev./Mean) × 100

Table 2.10 – Statistical Summary of Resilient Modulus Test Results Within Each Laboratory.

Laboratory	Mix Type	Test Temperature (°C)	Strain Level ($\mu\epsilon$)	Mean (ksi)	Standard Deviation	CV (%)
OSHD	AC20	25	50 100 150	328.40 283.07 277.12	42.72 28.72 28.04	13.00 10.14 10.12
	CA(P)-1	25	50 100 150	245.92 229.25 226.10	34.28 23.38 24.87	13.94 10.20 11.00
	CA(P)-1*	25	50 100 150	263.26 244.46 230.05	17.17 13.68 23.86	6.52 5.60 10.37
OSU	AC20	25	50 100 150	310.74 287.81 267.26	26.20 22.47 35.59	8.43 7.81 13.30
	AC20*	25	50 100 150	368.69 326.96 303.22	17.05 17.92 22.31	4.62 5.48 7.36
	AC20	0	50 100 150	2011.04 1950.97 1894.68	315.87 264.76 221.24	15.70 13.60 11.70
	CA(P)-1	25	50 100 150	299.38 257.80 251.81	19.48 16.16 16.01	6.51 6.27 6.36
	CA(P)-1*	25	50 100 150	331.38 297.14 273.03	28.88 20.16 15.79	8.71 6.78 5.78
	CA(P)-1	0	50 100 150	1850.46 1885.88 1863.58	205.61 185.33 125.94	11.10 9.80 6.80

* Originally scheduled to be tested at 0°C.

Table 2.11 - Statistical Summary of Fatigue Test Results.

Mix Type	Test Temperature (°C)	Failure Criteria	Mean	Standard Deviation	CV (%)	Number of Samples
AC20 Voids: 2.7 - 3.5 %	25	Initial Modified Perm Def	2465 2662 2380	346 535 531	14.0 20.1 22.3	12 6 6
	0	Modified	3138	3024	96.4	5
CA(P)-1 Voids: 2.1 - 3.6 %	25	Initial Modified Perm Def	9441 4537 4187	3865 846 830	40.9 18.6 19.8	12 6 6
	0	Modified	8262	7017	84.9	5

the most part, not significantly different. That is, it was shown that the OSHD laboratory modulus test results could not be satisfactorily reproduced at the OSU laboratory. Results of modulus tests within each laboratory, however, were determined to be quite repeatable as indicated by the low coefficients of variation which ranged between about 5 and 14% in both laboratories.

The significant differences between laboratories that are not apparent within laboratories would suggest the differences lie in the manner in which the moduli are determined in each laboratory. That is, the two laboratories use different test conditions and procedures. Although the exact effects of these differences are not well understood, it is clear that the equipment and procedures need to be better standardized.

Fatigue Testing. For fatigue testing no comparison between laboratories is possible since these tests were conducted exclusively at OSU. Thus, only the repeatability within the OSU laboratory is addressed. The most notable result is that the modified failure criterion significantly improved the repeatability of fatigue results for the CA(P)-1 mix at the 25°C temperature. At this temperature the repeatability is satisfactory for both mix types when using the modified failure criterion. Tests conducted at the 0°C temperature, however, result in unsatisfactory repeatability for both mix types. It should be noted that all of the specimens tested for fatigue at the low (0°C) temperature experienced brittle failure. In all cases, there was strong visual evidence that the failure was an adhesive one between the asphalt cement and the aggregate. This was also evidenced in the specimens tested at the 25°C temperature but not nearly to the extent evidenced in the specimens tested at the 0°C temperature. This may have contributed to the high variability in the fatigue test results at the low (0°C) temperature.

It should also be noted that approximately half of the samples failed on one side (the side which corresponds to the bottom of the specimen during compaction). This was observed during fatigue testing only at the 25°C temperature. This would suggest there may have existed "bridging" and segregation in the specimens during compaction. This, in turn, may have contributed to some variability in the fatigue results.

One unexpected result from the fatigue testing at the two different temperatures contradicts the commonly accepted theory that asphaltic concrete fails more rapidly at lower temperatures. Results in Table 2.11 show that fatigue life actually appears to be greater at the lower temperature. This trend is shown for both types of material. For the AC20 mix, the five tests at 0°C averaged 3138 repetitions while the six tests at 25°C averaged 2662 repetitions. For the CA(P)-1 mix, the five tests at 0°C averaged 8262 repetitions while the six tests at 25°C averaged 4537 repetitions.

Two different factors could partially explain this unexpected result: (1) the variability of cold temperature fatigue testing is so great that it is not possible to place full confidence in the results; and (2) different pieces of equipment were used for the two test temperatures (i.e., the 25°C samples were tested with a pneumatically actuated device while the 0°C samples were tested with a hydraulically actuated device). The major difference that would be expected to affect the results is that the waveforms of the two devices are different. That is, the cold temperature samples were tested using a haversine while the warm temperature samples were tested using a square wave. Further study would be required to determine how the results are affected by this difference in load waveforms.

3.0 Conclusions and Recommendations

3.1 Conclusions

The following conclusions appear to be warranted as a result of the contents of this paper:

1. Modulus test results are highly repeatable within the OSHD or the OSU laboratory.
2. Modulus test results are, for the most part, not reproducible between the OSHD and OSU laboratories. The cause of the differences appear to lie in the test conditions, procedures, and apparatus used to determine resilient modulus of asphalt concrete specimens.
3. Fatigue test results at 25°C can be highly to moderately repeatable providing that the improved criteria are used to establish failure.
4. Repeatability of fatigue tests at 0°C was found to be very poor. This is not too surprising since others (5,6,7,8,9) have reported poor repeatability at low temperatures.

3.2 Recommendations

The following recommendations appear to be warranted as a result of the contents of this paper:

1. Comparison of modulus test results between the OSHD and OSU laboratories are not warranted. This is primarily due to the significant differences in test conditions, procedures, and test apparatus used to measure resilient modulus. These differences need to be resolved as soon as possible.

2. Sample preparation (i.e., compaction) should be carried out such that segregation and "bridging" does not occur.
3. Additional fatigue testing should be carried out with improved temperature control to further investigate the poor repeatability of fatigue results at the 0°C temperature.

4.0 References

1. SCHOLZ T, et al, Developement of improved mix design and construction procedures for cold in-place recycled pavements. Final Report, Vol. III, FHWA-OR/RD-89-01. June 1988.

2. SCHOLZ T, 1986 performance evaluation report: Lava Butte Road - Fremont Junction Highway. Transporation Research Report 87-27. June 1987.

3. ROGGE DF, et al. Effect of polymer modifiers on asphalt properties. Interim Report, Executive Summary, FHWA-OR/RD-89-02. June 1988.

4. ANNUAL BOOK OF ASTM STANDARDS. Road and paving materials; traveled surface characteristics. Vol 04.03

5. EPPS JA, Influence of mixture variables on the flexural fatigue and tensile properties of asphalt concrete. Graduate report. ITTE, University of California, Berkeley. September, 1968.

6. ADEDIMILA AS and KENNEDY TW, Fatigue and resilient characteristics of asphalt mixtures by repeated-load indirect tension test. Interim report, CFHR 3-9-72-183-5, University of Texas at Austin. August 1975.

7. FINN FN, Factors involved in the design of asphaltic pavement surfaces. NCHRP Report 39. 1967.

8. MONISMITH CL, et al, Asphalt mixture behavior in repeated flexure: a study of an in-service pavement near Morro Bay, California. Report No. TE-67-4, ITTE, University of California, Berkeley. 1967.

9. VALLERGA BA, et al, Effect of asphalt aging on the fatigue properties of asphalt concrete. Proceedings. Second International Conference on the Structural Design of Asphalt Pavements. University of Michigan. 1967.

APPENDIX A

Sample Preparation (Including Job-Mix Formula)

The laboratory-fabricated specimens were compacted in accordance with AASHTO T-247 (ASTM D1561) and having the following job-mix formula:

Sieve Size	Percent Passing	Oil Content (%)	Lime Content (%)
3/4 1/2 3/8 1/4 # 4 #10 #40 #200	100.0 86.3 73.5 59.0 49.3 30.0 12.2 3.5	5 (24 specimens with AC20 and 24 specimens with CA(P)-1)	1 (all 48 specimens)

Material Type	Sample ID	Bulk Gravity	Rice Gravity	% Voids
AC20	1	2.316	2.400	3.50
	2	2.329	2.400	2.96
	3	2.328	2.400	3.00
	4	2.324	2.400	3.17
	5	2.323	2.400	3.21
	6	2.326	2.400	3.08
	7	2.330	2.400	2.92
	8	2.336	2.400	2.67
	9	2.326	2.400	3.08
	10	2.329	2.400	2.96
	11	2.336	2.400	2.67
	12	2.316	2.400	3.50
	Mean:	2.326		3.06
	Std. Dev.:	0.0064		0.2646
CA(P)-1	13	2.345	2.395	2.09
	14	2.316	2.395	3.30
	15	2.340	2.395	2.30
	16	2.322	2.395	3.05
	33	2.344	2.395	2.13
	34	2.310	2.395	3.55
	35	2.333	2.395	2.59
	36	2.322	2.395	3.05
	37	2.339	2.395	2.34
	38	2.320	2.395	3.13
	39	2.337	2.395	2.42
	40	2.332	2.395	2.63
	Mean:	2.330		2.72
	Std. Dev.:	0.0116		0.4854

APPENDIX B

Fatigue Test Procedure

1.0 INTRODUCTION

1.1 Scope

This appendix describes the procedure used to determine the fatigue life of laboratory-fabricated and field-recovered bituminous mixtures. The described procedure is essentially an extension of the Standard Method of Indirect Tension Test for Resilient Modulus of Bituminous Mixtures[1] (ASTM D4123-82). Other applicable documents include ASTM standards:

D1559 -- Test Method for Resistance to Plastic Flow of Bituminous Mixture Using Marshall Apparatus.

D1561 -- Method of Preparation of Bituminous Mixture Test Specimens by Means of California Kneading Compactor.

D3387 -- Test for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM).

D3496 -- Method for Preparation of Bituminous Mixture Specimens for Dynamic Modulus Testing.

D3515 -- Specifications for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures.

1.2 Summary of Procedure

The repeated-load indirect tensile test for determining the resilient modulus and fatigue life of bituminous mixtures is conducted by application of compressive loads in the form of a pulse, haversine, square, or other suitable waveform. The load is applied in the vertical diametral plane of a cylindrical asphalt concrete specimen as shown in Figure B.1. The magnitude of the repeated-load is the load that results in a specified recoverable horizontal deformation or tensile strain as determined via ASTM D4123.

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[1]Annual Book of ASTM Standards, Vol. 04.03

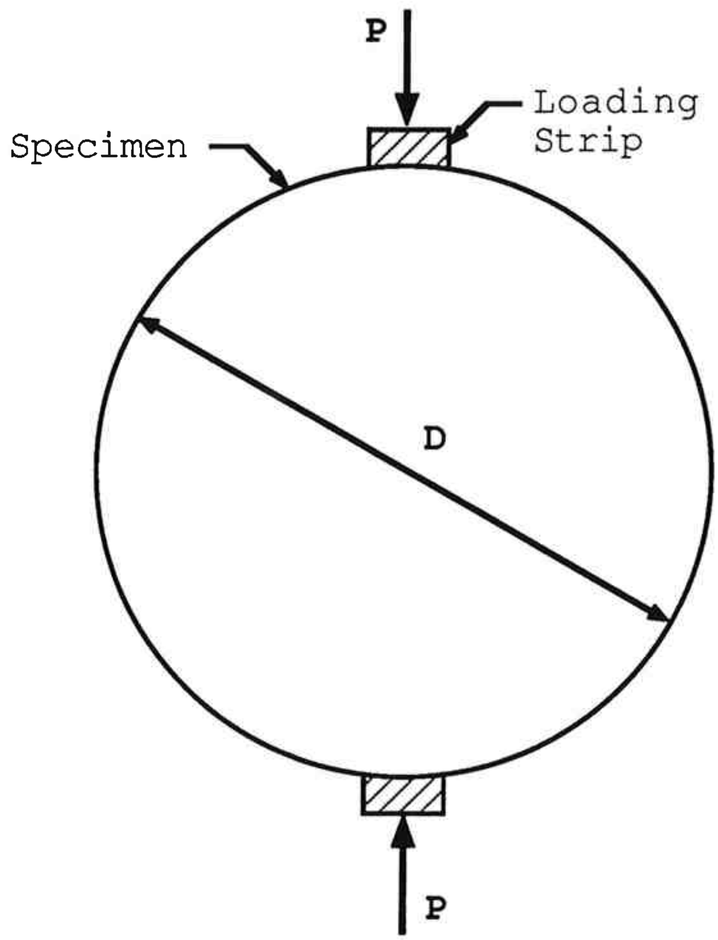


Figure B.1 – Loading of a Cylindrical Asphalt Concrete Specimen in the Repeated Load Indirect Tensile Test.

The number of load applications that results in a specified amount of permanent horizontal deformation is the fatigue life of the specimen. Typical amounts of permanent horizontal deformation range between 0.28 and 0.36-in.

1.3 Significance and Use

Fatigue values (i.e., fatigue life) can be used to evaluate the relative performance of asphaltic concrete materials as well as be used as input for pavement thickness design or pavement evaluation and analysis. The test can also be used to study the effects of temperature, repeated-load magnitude, loading frequency and duration, etc. However, since the test is destructive, tests cannot be repeated on the same specimen as can be done for resilient modulus.

2.0 TEST PROCEDURE

2.1 Test Apparatus

The apparatus to perform the indirect tensile fatigue test should conform to that specified in ASTM D4123 with the added ability to count and record the number of load applications. In addition, the apparatus should have the ability to automatically discontinue load applications when the specified amount of permanent horizontal deformation has occurred.

2.2 Specimen Preparation

2.2.1Laboratory-Fabricated Specimens. Prepare laboratory-fabricated specimens in accordance with ASTM Methods D1559, D1561, D3387, or D3496. The resulting specimens should have a height of at least 2-in. and a diameter of 4-in. for aggregate having a maximum size of 1-in. For aggregate having a maximum size of 1.5-in., the height should be at least 3-in. and the diameter should be 6-in.

2.2.1Core Specimens. Core specimens should have relatively smooth and parallel surfaces. Height and diameter requirements specified for the laboratory-fabricated specimens are applicable to cores specimens.

2.3 Failure Criteria

As previously mentioned, the fatigue life is the number of load applications required to induce a specified amount of permanent horizontal deformation. Failure criteria typically range between 0.28 and 0.36-in. which roughly corresponds to the size of the crack developed in the specimen during fatigue. Experience has shown, however, that failure criteria greater than about 0.35-in. may result in the test specimen failing dramatically ("exploding") when the induced tensile strain is on the order of 100 microstrain or greater. That is, when the specimen is near failure, the sample may explode due to the failure criterion (permanent horizontal deformation) being too large.

Once the failure criterion is selected, it can be determined during the fatigue test by means of an electronic circuit which is closed with lead-based foil tape (burglar alarm tape for glass windows). When the foil tape breaks the circuit is opened and load applications discontinue. The amount of permanent horizontal deformation that occurs before the foil tape breaks is set by the length of loop placed in the foil tape on both sides of the specimen (see Figure B.2).

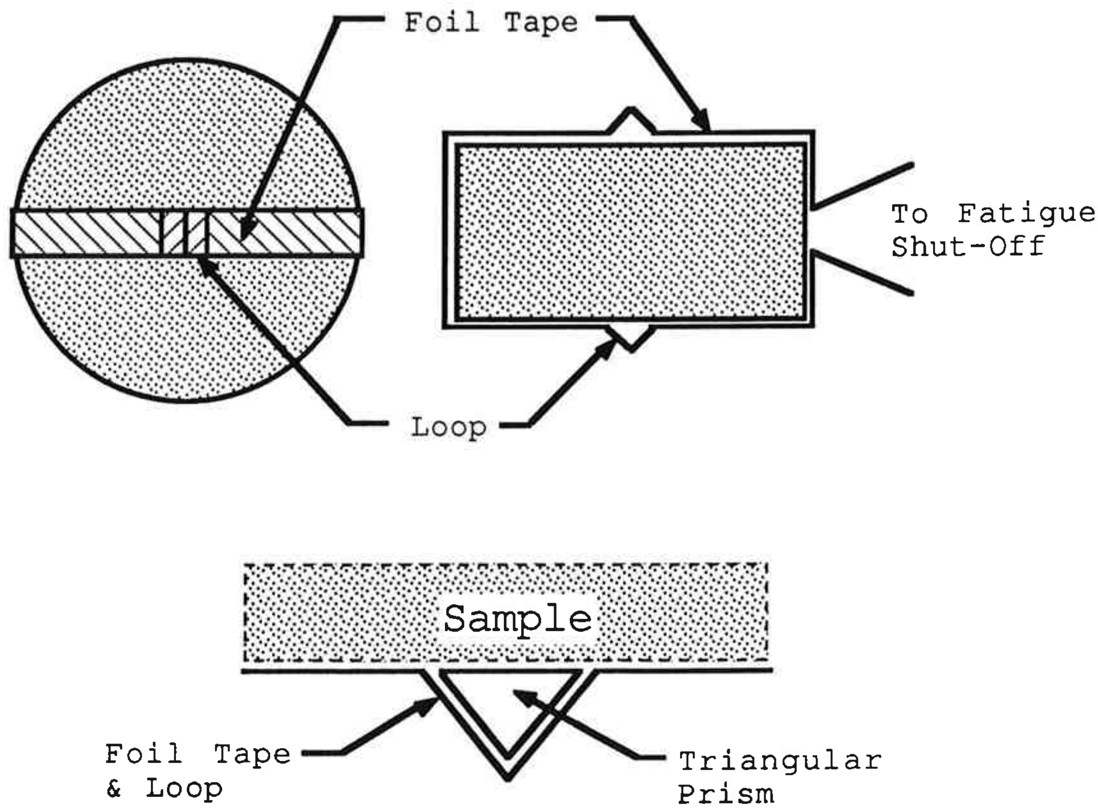


Figure B.2 – Asphalt Concrete Specimen with Foil Tape Having Loops on Both Sides of the Specimen.

2.4 Fatigue Test

The indirect tensile fatigue test is conducted as follows:

1. Determine loading conditions (i.e., load frequency and duration), test temperature, initial recoverable tensile strain, and amount of permanent horizontal deformation to be used in the determination of the fatigue life.

2. Determine the load magnitude required to induce the specified recoverable tensile strain via ASTM D4123.

3. Place lead-based foil tape around the diametral axis perpendicular to the loading axis such that the foil tape has two loops of length corresponding to the specified amount of permanent horizontal deformation (see Figure B.3a). The foil tape must not connect end-to-end since this would cause a short circuit.

4. Secure the foil tape by means of hot glue or other appropriate adhesive as shown in Figure B.3a.

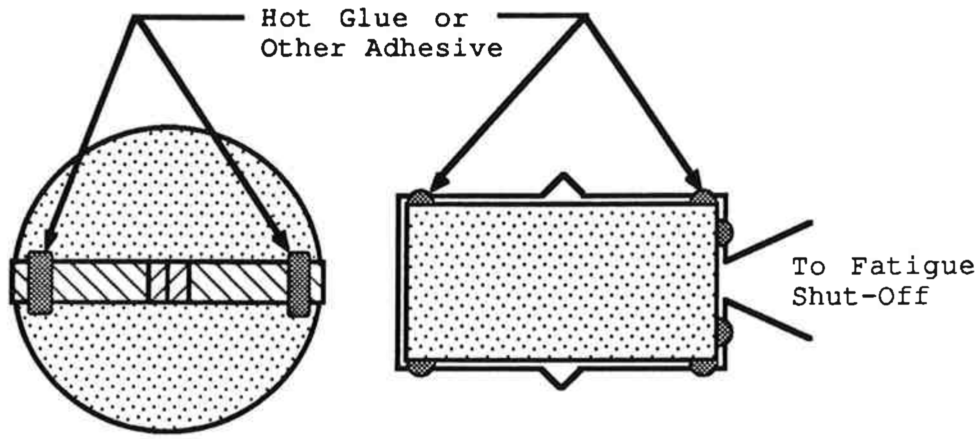
5. Solder leads to each end of the foil tape and connect the leads to a circuit that continues load applications while closed and discontinues loading when open.

6. Place the test specimen in the test apparatus such that the line of the foil tape is perpendicular to the line of loading as shown in Figure B.3b.

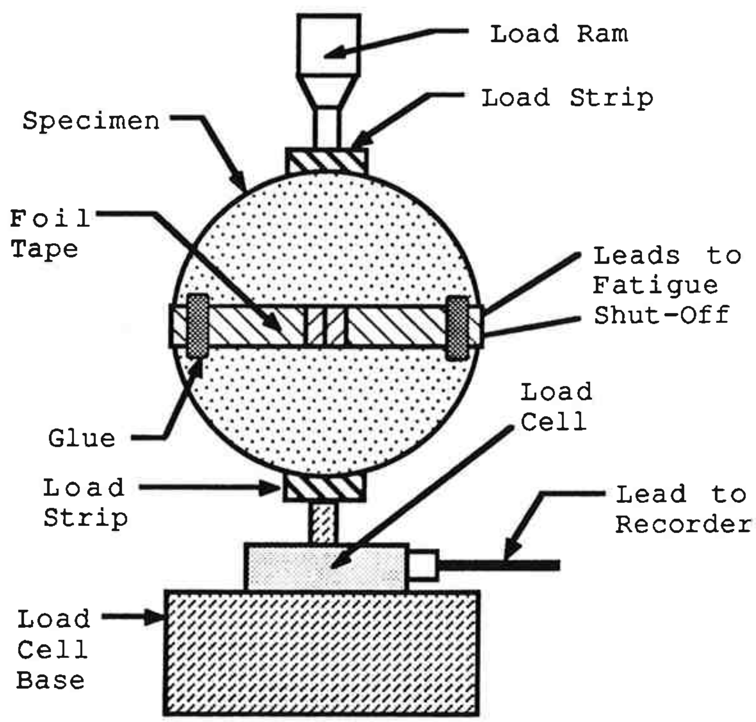
7. Apply the static load that was applied when determining the load magnitude to induce the specified recoverable tensile strain.

8. Apply a repeated-load such that the magnitude of the load corresponds to that which induced the specified amount of recoverable tensile strain.

9. Count and record the number of load applications required to break the foil tape.



a) Location of Glue



b) Orientation of Fatigue Specimen

Figure B.3 - Fatigue Specimen Set Up