U.S. Department
of Transportation
**Federal Highway
Administration**

Asphalt Binder Cracking Device to Reduce Low-Temperature Asphalt Pavement Cracking: Final Report

Highways for LIFE Technology Partnership Program
Federal Highway Administration

JULY 2010
FHWA-HIF-11-029

FOREWORD

This report summarizes research into use of the Asphalt Binder Cracking Device (ABCD), a new empirical test method for evaluating the low-temperature cracking potential of asphalt binder. The ABCD test method has been adopted as a Provisional Standard by the American Association of State Highway and Transportation Officials. This report presents the results of two interlaboratory studies that examined the ABCD's precision and documents the modification of the ABCD procedure to achieve greater precision.

The refinement of the late-stage prototype and inter-laboratory study of the ABCD was supported by a grant from the Highways for LIFE Technology Partnerships Program. The Technology Partnerships Program provided grants to assist general industry make the leap from promising late-stage prototypes to market-ready products and promoted partnerships with State and local highway agencies to demonstrate the technologies under real-world conditions.

This report will be of interest to State and local departments of transportation, Federal Highway Administration division offices, highway research institutions, asphalt manufacturers, and highway construction contractors.

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No. FHWA-HIF-11-029	**2. Government Accession No.**	**3. Recipient’s Catalog No.**

4. Title and Subtitle *Asphalt Binder Cracking Device to Reduce Low-Temperature Asphalt Pavement Cracking: Final Report*	**5. Report Date** July 2010
	6. Performing Organization Code
7. Author(s) Sang-Soo Kim, Ph.D., P.E.	**8. Performing Organization Report No.**
9. Performing Organization Name and Address EZ Asphalt Technology, LLC 340 W. State Street Unit #2, 142 Innovation Center Athens, OH 45701	**10. Work Unit No.**
	11. Contract or Grant No. DTFH61-08-G-00005
12. Sponsoring Agency Name and Address Highways for LIFE Program Office, Office of Infrastructure, Federal Highway Administration, U.S. Department of Transportation, 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report; 2008–2010
	14. Sponsoring Agency Code HIHL

15. Supplementary Notes

Agreement Officer: Freida Byrd, Office of Acquisition Management, Federal Highway Administration (HAAM-40)
Agreement Officer Technical Representative: Julie Zirlin, Highways for LIFE, Office of Infrastructure, Federal Highway Administration (HIHL)

16. Abstract:

As part of a national initiative sponsored by the Federal Highway Administration under the Highways for LIFE program, EZ Asphalt Technology was awarded a grant to refine the Asphalt Binder Cracking Device (ABCD) test method and conduct an interlaboratory study. This report documents the results of two interlaboratory studies that examined the ABCD’s precision and documents the modification of the ABCD procedure to achieve greater precision.

The ABCD is an easy-to-use device for determining the overall low-temperature cracking potential of an asphalt binder. The report presents results of the ABCD interlaboratory study (ILS), a second ILS comparing use of the ABCD with Bending Beam Reflectometer (BBR) testing, and a third study that modified the ABCD testing procedure to improve precision of ABCD testing. Data from 23 laboratories participating in the ABCD testing are presented.

Results of the ABCD and BBR testing indicated that the precision estimates of ABCD cracking temperature and those of the BBR critical temperature were comparable. The No-Trim ABCD test procedure developed during the project is expected to improve the precision of ABCD test results.

17. Key Words asphalt pavement cracking, Asphalt Binder Cracking Device, asphalt binder testing , Bending Beam Rheometer, low temperature cracking	**18. Distribution Statement** No restrictions. This document is available to the public through http://www.fhwa.dot.gov/hfl/.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 44	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

EXECUTIVE SUMMARY

The overall scope of the Highways for LIFE grant to EZ Asphalt Technology was to refine the Asphalt Binder Cracking Device (ABCD) test method and to conduct an ABCD interlaboratory study (ILS). During Phase 1, ABCD test equipment and test procedures were refined. During Phase 2, five units of ABCD were manufactured and tested in an ABCD ILS. Thirty-one laboratories volunteered for the ABCD ILS. Following manufacturing and testing, ABCD units were delivered to the first five participating laboratories. As a laboratory finished the ILS testing, the unit was repacked and shipped to the next waiting laboratory.

Due to the larger than expected number of volunteering laboratories, the original binder samples prepared for this ABCD ILS ran out in the middle of ILS testing. Replacement binder samples were used for the later part of ABCD ILS testing. However, the analyses of ABCD ILS were based on the data from the 23 laboratories that used the original binder samples. With very limited experience with the ABCD equipment and test procedure, almost all participating laboratories were able to complete the ABCD ILS successfully without major difficulty. Ten laboratories also volunteered to participate in the Bending Beam Rheometer (BBR) Critical Temperature ILS. The results of the ABCD and BBR studies indicated that the precision estimates of ABCD cracking temperature and those of the BBR critical temperature were comparable.

The standard deviation of the ABCD cracking temperature, strain jump, and fracture strength for single-operator ABCD tests were 0.95 °C (1.71 °F), 5.48 $\mu\varepsilon$, and 0.86 MPa (125 psi), respectively. The standard deviation of the ABCD cracking temperature, strain jump, and fracture strength for multilaboratory ABCD tests were 1.36 °C (2.45 °F), 7.21 $\mu\varepsilon$, and 1.13 MPa (163.9 psi), respectively. The standard deviations of the BBR critical temperature for single-operator and multilaboratory tests were 0.44 °C (0.79 °F) and 0.75 °C (1.35 °F), respectively, when the critical temperatures were determined from an interpolation process where the BBR test results from two adjacent grading temperatures bracket the critical values of creep stiffness and m-value. The precision estimates of the BBR critical temperature are better than those of the ABCD cracking temperature. However, the BBR critical temperature alone cannot estimate the proper cracking temperature of asphalt binder. Strength testing must be performed and combined with the BBR test results. Then, the precision of the resulting cracking temperature by BBR would be similar to that of ABCD cracking temperature.

To further improve the precision of ABCD test results, the No-Trim ABCD test procedure was developed. An experiment performed with a limited number of binders showed that the steps for trimming and lubrication of the silicone mold in the current ABCD procedure could be eliminated. Based on these findings, a revised ABCD test procedure was developed and is presented in this report. The No-Trim ABCD test procedure is expected to improve the precision of ABCD test results, especially the multilaboratory precision estimates.

The American Association of State Highway and Transportation Officials (AASHTO) Committee has voted to adopt the ABCD test method as a provisional test method. The ABCD test procedure will be included in a 2011 edition of AASHTO specifications.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. SIGNIFICANCE OF THE ASPHALT BINDER CRACKING DEVICE

Low-temperature cracking is one of the major failure modes in asphalt pavements and is largely influenced by asphalt binder properties. The Asphalt Binder Cracking Device (ABCD) is a new test method determining the low-temperature cracking potential of asphalt binder in a field-like condition without prior knowledge of rheological properties, tensile strength, and coefficient of thermal expansion/contraction (CTE) of the binder.(1,2,3) For the ABCD test, a circular asphalt binder specimen is prepared on the outside of an Invar ring 50.8 mm (2.00 in.) in diameter. Invar is a steel alloy with near-zero CTE. As the temperature is lowered, the thermal stress within the asphalt specimen increases until fracture. The data from the instrumented sensors are used to determine the temperature and strength at the moment of fracture.

The current Performance-Graded (PG) binder grading system for low temperature is based on mechanistic-empirical analysis of thermal cracking. However, some of the important binder properties needed in the analysis, such as CTE and tensile strength, are not readily available due to the lack of adequate test equipment and method.(4) ABCD is a simple and easy-to-use testing device that can provide the overall low-temperature cracking potential of an asphalt binder. ABCD can be used by itself or in conjunction with other test methods to accurately grade asphalt binders for low-temperature performance. Findings from previous ABCD studies are summarized below.

The ABCD cracking temperatures were highly correlated with the performance of test pavements.(1) For field validation, ABCD tests were performed on asphalt binders used in three well-known test pavements: Elk County, Pennsylvania, Test Road; Lamont, Alberta, Test Road; and SPS-9A sections on Highway 17, Ontario. In all cases, the ABCD cracking temperatures correlated consistently better with crack severities of test pavements than AASHTO M 320 critical temperatures, as shown in table 1.

Table 1. Coefficient of Determination (R^2): Cracking or Critical Temperature Versus Cracking Index of Test Pavements

Test Road	ABCD Cracking Temperature	AASHTO Critical Temperature M 320 Table 1 (BBR)	M 320 Table 2 (BBR+DT)
Elk County, PA	0.94	0.21	0.95
Lamont, AB	0.92	0.79	0.76
Highway 17, ON	0.80	0.92	0.56

BBR = Bending Beam Rheometer; DT = Direct Tension

The ABCD could measure polymer-modification effects on low-temperature thermal cracking. It is well known that the polymer-modified asphalts (PMAs) perform better for low-temperature cracking than unmodified asphalts. However, when PMAs are tested with the Bending Beam Rheometer (BBR), the effects of the polymer modification on the low-temperature performance of binders cannot be accurately determined. In a laboratory study, styrene-butadiene-styrene (SBS) polymer was added at varying concentrations and tested with both the BBR and the ABCD.(1) While BBR results (AASHTO M 320 Table 1) indicated that the polymer addition did not improve the low-temperature grade of the binder, ABCD results showed a clear and gradual decrease in the ABCD cracking temperature as the polymer concentration increased, as shown in figure 1.

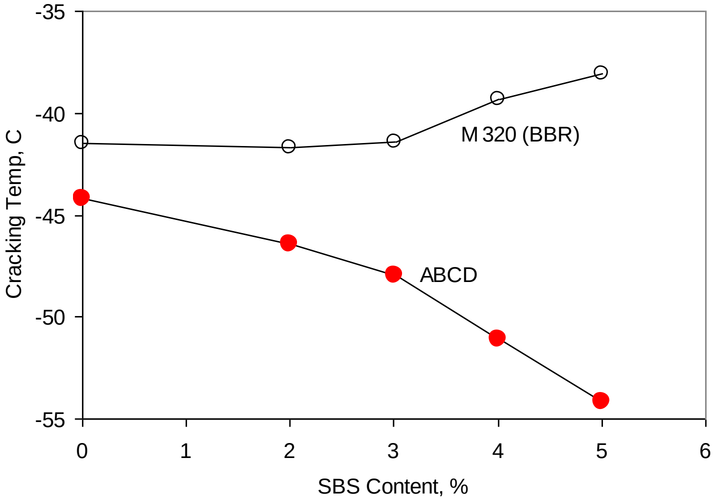

Figure 1. Effect of SBS concentration on continuous PG low-temperature grade (AASHTO M 320 Table 1) and ABCD cracking temperature.

ABCD can measure the fracture strength of asphalt binders at the cracking temperature. The strain jump measured in the ABCD test is defined as the difference between compressive strains of the ABCD ring before and after thermal cracking. Using force equilibrium, the fracture strength at the ABCD cracking temperature can be estimated from the strain jump. As shown in figure 2, ABCD was able to measure the gradual increase of fracture strength with the increase of SBS concentration in asphalt binder.

The ruggedness study of the ABCD test procedure completed during Phase 1 showed that the ABCD test was robust against reasonable variation of cooling rate, specimen dimensions, and other test variables.(5) ABCD test results were not significantly affected by the expected variation of these test conditions.

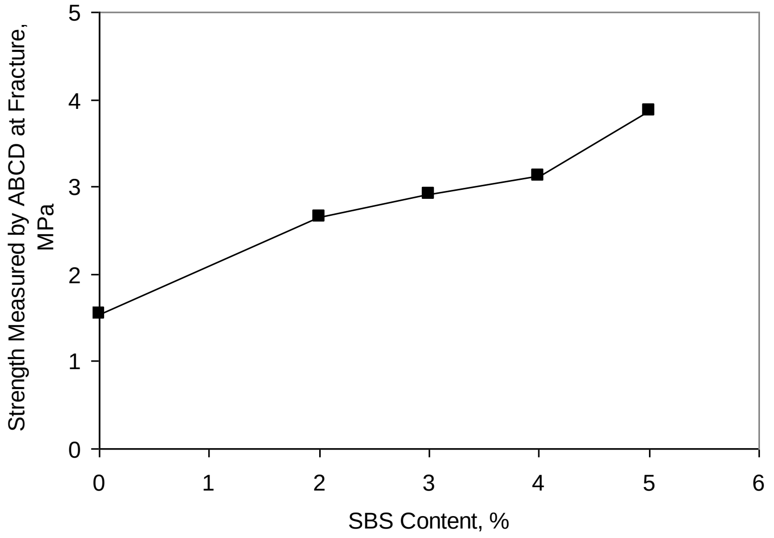

Figure 2. Effect of SBS concentration on binder fracture strength measured by the ABCD.

CHAPTER 2. PROJECT OVERVIEW

The main objectives of this project were to refine the ABCD test method and to conduct the ABCD interlaboratory study (ILS). During Phase 1, ABCD test equipment and test procedures were refined. The ABCD ruggedness test was also completed and reported.(5) One of the major refinements in the ABCD test procedure made during Phase 1 was the cooling rate. The typical pavement cooling rate is considered to be about 5 °C/hr (9 °F/hr) or slower.(6) During the initial development of the ABCD, the rate of 10 °C/hr (18 °F/hr) was used as for other similar test methods. To study the effects of cooling rate during Phase 1, six binder types and five cooling rates (1 °C/hr, 3 °C/hr, 10 °C/hr, 20 °C/hr, and 40 °C/hr [1.8 °F/hr, 5.4 °F/hr, 18 °F/hr, 36 °F/hr, and 72 °F/hr]) were used for ABCD tests. For the cooling rate of 3 °C/hr (5.4 °F/hr) or faster, the effects of the cooling rate on ABCD cracking temperatures were relatively small and the rank of binder type in the cracking temperature did not change. On average, the increase of the cooling rate by 1 °C/hr (1.8 °F/hr) increased the cracking temperature by about 0.07 °C (0.13 °F). When the cooling rate was lowered to 1 °C/hr (1.8 °F/hr), the changes in the cracking temperature were asphalt dependent; some binders showed significantly decreased cracking temperature and some changed little. At this slow cooling rate, the effects of physical hardening seemed to have effects on the cracking temperature. The standard deviation of the cracking temperature remained small up to the rate of 20 °C/hr (36 °F/hr). At 40 °C/hr (72 °F/hr), the standard deviation increased significantly. Based on this finding, 20 °C/hr was the rate chosen for the ABCD testing, and it was used for all Phase 2 activities.

Two main tasks planned for Phase 2 of the program were manufacturing five units of ABCD and conducting an ABCD ILS. For the Superpave low-temperature grade of asphalt binder, the BBR test has been used in practice. The BBR critical temperature for thermal cracking is the warmer temperature between temperatures where the BBR creep stiffness reaches a critical stiffness of 300 MPa (43.51 ksi) or where the slope of log stiffness versus log time plot, known as m-value, reaches 0.300. The current standard test method (AASHTO T 313) describes the BBR test procedures and also provides the precision estimates for the BBR creep stiffness and m-value, but not for the BBR critical temperature. Before Phase 2 began, the program review panel recommended comparing the precision estimates of ABCD cracking temperature with those of the BBR critical temperature. In addition to the ABCD ILS, another ILS was conducted for BBR critical temperature. Both studies followed the guideline outlined in ASTM C802, "Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials." Three binders with different levels of stiffness were chosen (low, medium, and high stiffness; labeled as Lxx, Mxx, and Hxx, respectively). The low-stiffness binder was an unaged PG 70-28 SBS modified. The medium-stiffness binder was an unaged PG 76-22 SBS modified. The high-stiffness binder was an unmodified mixing stock with penetration 0–10 (equivalent of PG 88 + 6).

Table 2 lists the 31 laboratories that volunteered for the ABCD ILS, including 18 State and Federal Government laboratories, 1 Superpave Center, 1 Canadian Province Ministry of Transportation, 5 universities, and 6 private laboratories. Ten laboratories also participated in the BBR critical temperature ILS. Because there were more ILS participants than expected, the binder samples ran out after the first 23 ABCD ILS laboratories had participated, and replacement binder samples with the same PG grade were used for the remaining laboratories. For determination of ABCD precision estimates, however, only data from the first 23 laboratories were used.

This report summarizes both the ABCD ILS and the BBR Critical Temperature ILS. In an effort to improve the precision of ABCD test results, the No-Trim ABCD test procedure was developed. This procedure and results obtained from No-Trim ABCD tests are discussed in this report. The appendix presents the results of the No-Trim ABCD tests.

Table 2. Laboratories That Participated in the ABCD ILS

1	EZ Asphalt Technology
2	NC Superpave Center*
3	Ohio Department of Transportation (DOT)*
4	Virginia Department of Transportation
5	Iowa Department of Transportation
6	Montana Department of Transportation *
7	Florida Department of Transportation *
8	Vermont Department of Transportation *
9	Kansas Department of Transportation *
10	Oregon Department of Transportation
11	PRI Asphalt Technologies
12	New York Department of Transportation *
13	Minnesota Department of Transportation *
14	Massachusetts Department of Transportation *
15	Federal Highway Administration–Denver
16	Washington State Department of Transportation
17	Ontario Ministry of Transportation
18	Mathy Construction, Technical and Engineering Services
19	Western Research Institute
20	Texas Department of Transportation
21	Turner-Fairbank Highway Research Center *
22	U.S. Oil & Refining Co.
23	University of Massachusetts, Dartmouth
24	Alaska Department of Transportation, Anchorage
25	Alaska Department of Transportation, Fairbank
26	New Hampshire Department of Transportation
27	Michigan Technological University
28	University of Iowa
29	University of Rhode Island
30	University of Wisconsin, Madison
31	The Hudson Company

* Laboratory also participated in the BBR critical temperature ILS.

CHAPTER 3. ASPHALT BINDER CRACKING DEVICE INTERLABORATORY STUDY

For the ABCD ILS, each laboratory received instructions and the ABCD test procedure to review before receiving the ABCD unit and binder samples. After a few practice tests, each laboratory performed 3 ABCD runs of 4 specimens each (a total of 12 specimens) on each of the 3 binder grades.

Average ABCD cracking temperature and strain jump for each binder and each laboratory are presented in tables 3 and 4 and figures 3 and 4. ABCD strain jump (ε) at fracture may be converted into the fracture stress of the asphalt binder (σ_f) as follows:

$$\sigma_f = (K)\,\varepsilon \cdot E_{ABCD} \cdot A_{ABCD}/A_{binder}$$

where,

K = stress concentration factor, 2.02
E_{ABCD} = Young’s modulus of ABCD ring, 140 GPa (20,305 ksi)
A_{ABCD} = Cross-sectional area of ABCD ring, 22.6 x 10^{-6} m^2 (27.0 x 10^{-6} yd^2)
A_{binder} = Cross-sectional area of asphalt binder, 40.3 x 10^{-6} m^2 (48.2 x 10^{-6} yd^2)

To use the ABCD for accurate strength measurement, each ring should be calibrated for load–strain relationship. The ABCD rings used in this ILS were not calibrated. The precision of ABCD strain jump results may be improved when calibrated ABCD rings are used. For easy comparison, the Y-axis scales of figures 3 and 4 are kept the same for all three binders.

Before determining the precision of the test, ASTM C802 requires the operator to identify and remove erratic data by plotting variance versus lab, as shown in figures 5 and 6. Even though Lab 1 (EZ Asphalt laboratory) was the only laboratory with significant prior experience with ABCD testing, many labs produced lower variance for the ABCD test (meaning the results of three runs of one sample are similar). There are quite few noticeably large variance values. However, it is not clear if they are erratic data. Since the number of participating laboratories (23) was significantly larger than the recommended minimum (10), the effects of few data with the large variance values could be insignificant. Data analysis was performed without removing these data, and the precision estimates of ABCD test results would be conservative ones.

The statistical summary of the ABCD ILS results is presented in table 5. The ABCD cracking temperatures of three binders were significantly lower than the PG low-temperature grade since ABCD tests evaluated the low-temperature cracking potential of asphalt binder only. The addition of mineral aggregates in the asphalt binder would raise the cracking temperature. For all three binders, the within-lab variances of the ABCD cracking temperatures were similar and independent of the cracking temperature. The between-lab variance for the medium-stiffness binder is lowest ($s^2 = 1.19$), followed by the low-stiffness binder ($s^2 = 1.87$) and the high-stiffness binder ($s^2 = 2.58$). The low-stiffness binder seemed to deform easily during the trimming, transportation, and handling steps, resulting in larger variances than the medium-stiffness binder. The high-stiffness binder was extremely stiff at room temperature, making trimming unusually difficult and contributing to the large between-lab variance.

Two SBS-modified binders (PG 70-28 and PG 76-22) exhibited much larger strain jump than the unmodified high-stiffness binder (PG 88+6). The fracture strengths of the low-, medium-, and high-stiffness binders were estimated to be 6.5 MPa (943 psi), 6.3 MPa (914 psi), and 3.3 MPa (479 psi), respectively. The within-lab and the between-lab variances of the strain jump seemed larger for the binders with a larger strain jump. The SBS-modified binders, which showed about twice-larger strain jump than the unmodified binder, also had twice or more within-lab and between-lab variances.

The precision estimates of ABCD tests are given in table 6. When a single operator runs the ABCD test twice on the same sample, the acceptable range of two test results should be less than 2.69 °C (4.84 °F), 15.50 $\mu\varepsilon$, and 2.43 MPa (352.4 psi), for the ABCD cracking temperature, strain jump, and fracture strength, respectively. When two different operators at two different laboratories perform ABCD tests on the same sample, the acceptable range of two test results should be less than 3.85 °C (6.93 °F), 20.39 $\mu\varepsilon$, and 3.20 MPa (464.1 psi) for the ABCD cracking temperature, strain jump, and fracture strength, respectively.

Table 3. ABCD ILS Results: ABCD Cracking Temperature

	Cracking Temp (°C)					
	Average of 3 Runs			Standard Deviation (°C)		
Lab No.	PG70-28 (Lxx)	PG76-22 (Mxx)	PG88+6 (Hxx)	PG70-28 (Lxx)	PG76-22 (Mxx)	PG88+6 (Hxx)
1	-41.3	-40.0	-11.8	0.7	1.2	0.8
2	-40.3	-40.6	-11.0	1.6	1.6	2.7
3	-43.1	-40.1	-12.9	1.6	1.7	1.4
4	-40.3	-39.6	-11.7	1.0	0.6	0.8
5	-40.5	-40.4	-12.4	1.8	1.8	2.1
6	-41.7	-41.0	-14.9	2.2	2.3	1.3
7	-44.0	-42.3	-15.8	1.5	1.0	1.7
8	-42.7	-40.7	-14.7	4.2	2.6	0.8
9	-40.4	-40.0	-11.3	1.6	0.7	0.8
10	-44.8	-42.3	-13.4	1.9	1.0	0.9
11	-42.0	-40.9	-12.9	0.8	2.1	1.3
12	-41.3	-40.9	-12.0	2.0	1.2	0.9
13	-40.0	-39.4	-12.1	1.2	0.5	0.5
14	-42.4	-40.9	-11.6	2.9	1.3	0.7
15	-40.3	-39.6	-12.3	0.5	0.7	0.9
16	-40.5	-40.3	-12.2	1.2	1.5	0.7
17	-42.2	-41.3	-13.3	1.0	1.6	1.0
18	-42.7	-39.8	-11.6	1.3	1.0	1.9
19	-39.9	-38.8	-10.6	1.1	0.8	1.3
20	-39.4	-38.4	-7.9	1.2	1.7	3.6
21	-41.4	-41.0	-11.5	1.4	0.5	0.8
22	-41.0	-38.7	-12.2	2.1	1.9	0.6
23	-41.5	-42.4	-13.8	1.8	2.1	1.6
Average	**-41.5**	**-40.4**	**-12.3**	**1.6**	**1.4**	**1.3**

Table 4. ABCD ILS Results: ABCD Strain Jump

	Strain Jump (με)					
	Average of 3 Runs			Standard Deviation (με)		
Lab No.	PG70-28 (Lxx)	PG76-22 (Mxx)	PG88+6 (Hxx)	PG70-28 (Lxx)	PG76-22 (Mxx)	PG88+6 (Hxx)
1	42.9	45.0	19.6	8.5	11.7	2.5
2	36.1	31.2	13.1	9.5	8.4	6.5
3	36.4	31.6	18.2	13.7	10.5	6.5
4	38.8	44.1	23.5	6.6	4.5	3.3
5	36.4	38.4	16.4	6.6	10.1	6.2
6	35.5	28.1	15.6	12.2	15.8	7.7
7	52.3	41.6	24.7	12.7	13.6	5.1
8	36.7	21.5	16.1	20.6	8.9	3.7
9	33.3	39.4	22.0	4.7	10.0	4.7
10	68.0	57.6	37.4	17.9	33.9	11.6
11	36.1	33.9	21.0	6.9	10.4	4.3
12	39.6	50.6	21.5	11.9	7.5	5.0
13	37.0	39.9	22.2	4.5	2.7	2.2
14	43.2	41.1	15.3	20.3	7.6	2.2
15	38.7	43.2	21.9	4.0	3.7	3.6
16	33.9	45.8	24.3	18.2	16.3	6.1
17	46.0	47.6	26.1	4.9	6.8	3.3
18	47.6	39.5	18.1	6.1	7.6	5.2
19	43.7	33.5	16.9	21.3	6.8	4.9
20	32.8	26.9	21.3	16.2	10.5	14.9
21	49.1	53.5	22.4	5.6	4.0	4.3
22	42.0	36.0	17.7	5.1	7.0	1.9
23	36.4	42.0	16.0	14.4	16.5	5.4
Average	**41.0**	**39.6**	**20.5**	**11.0**	**10.2**	**5.3**

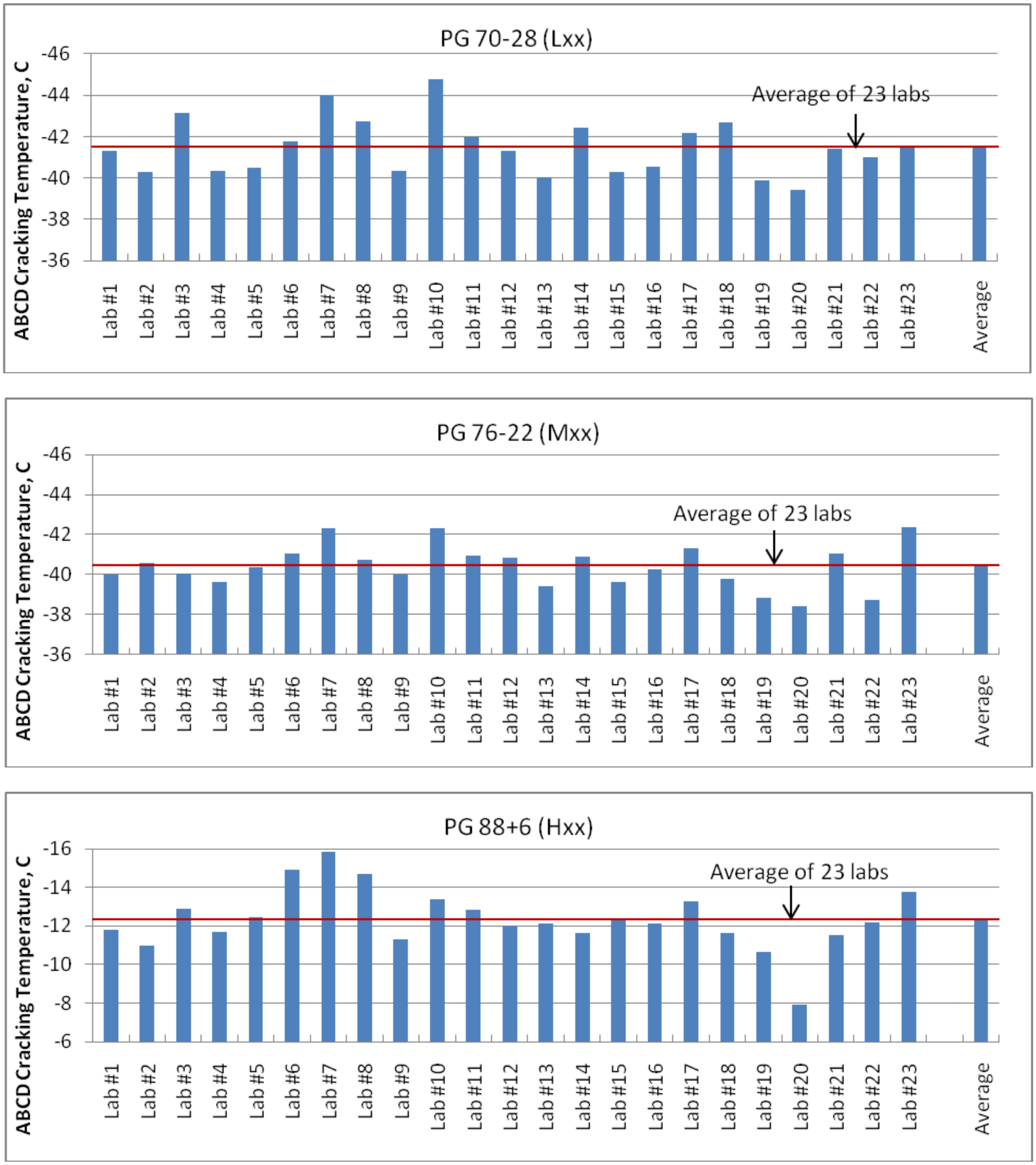

Figure 3. ABCD ILS Results: Average ABCD cracking temperatures.

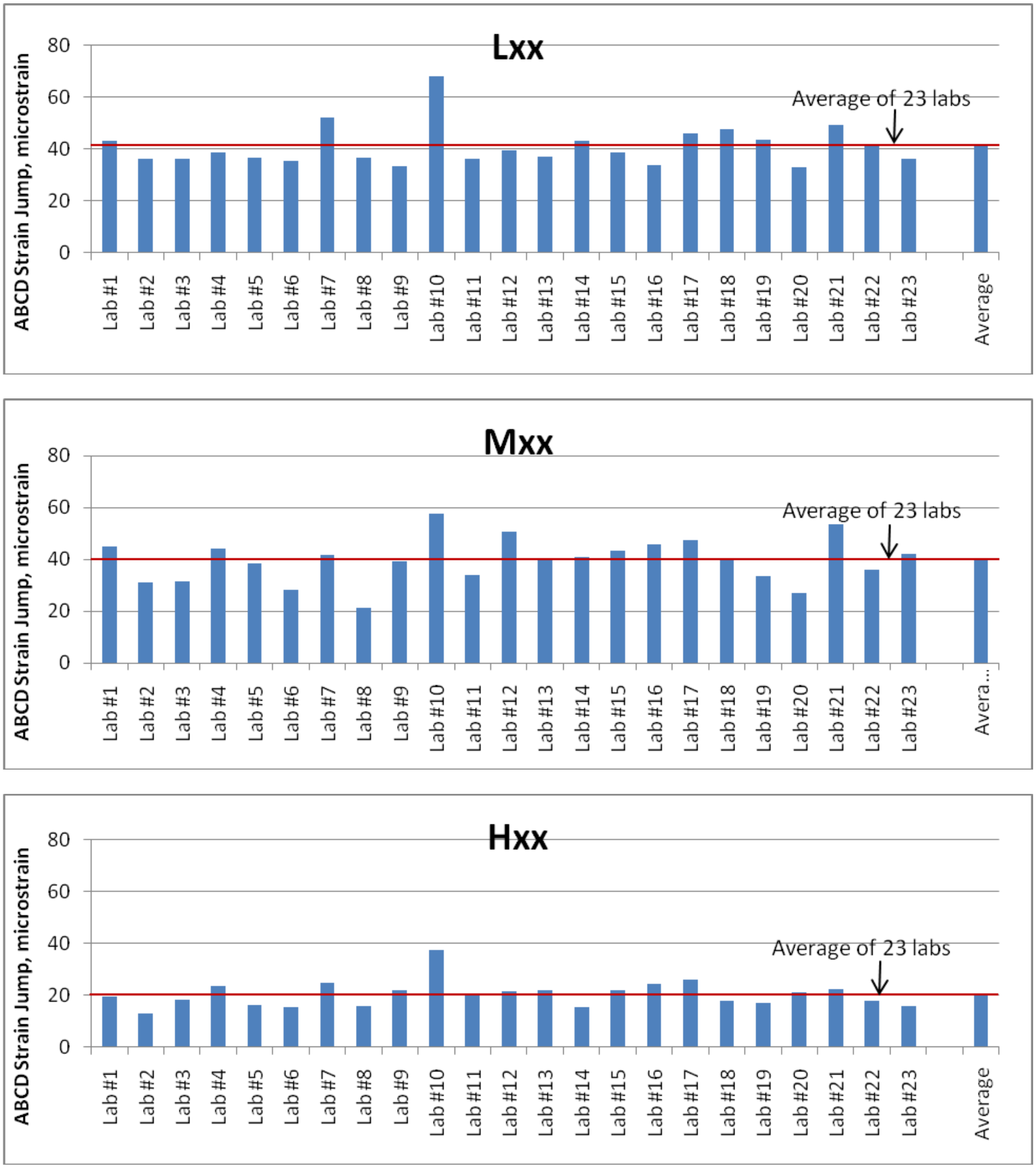

Figure 4. ABCD ILS Results: Average strain jump.

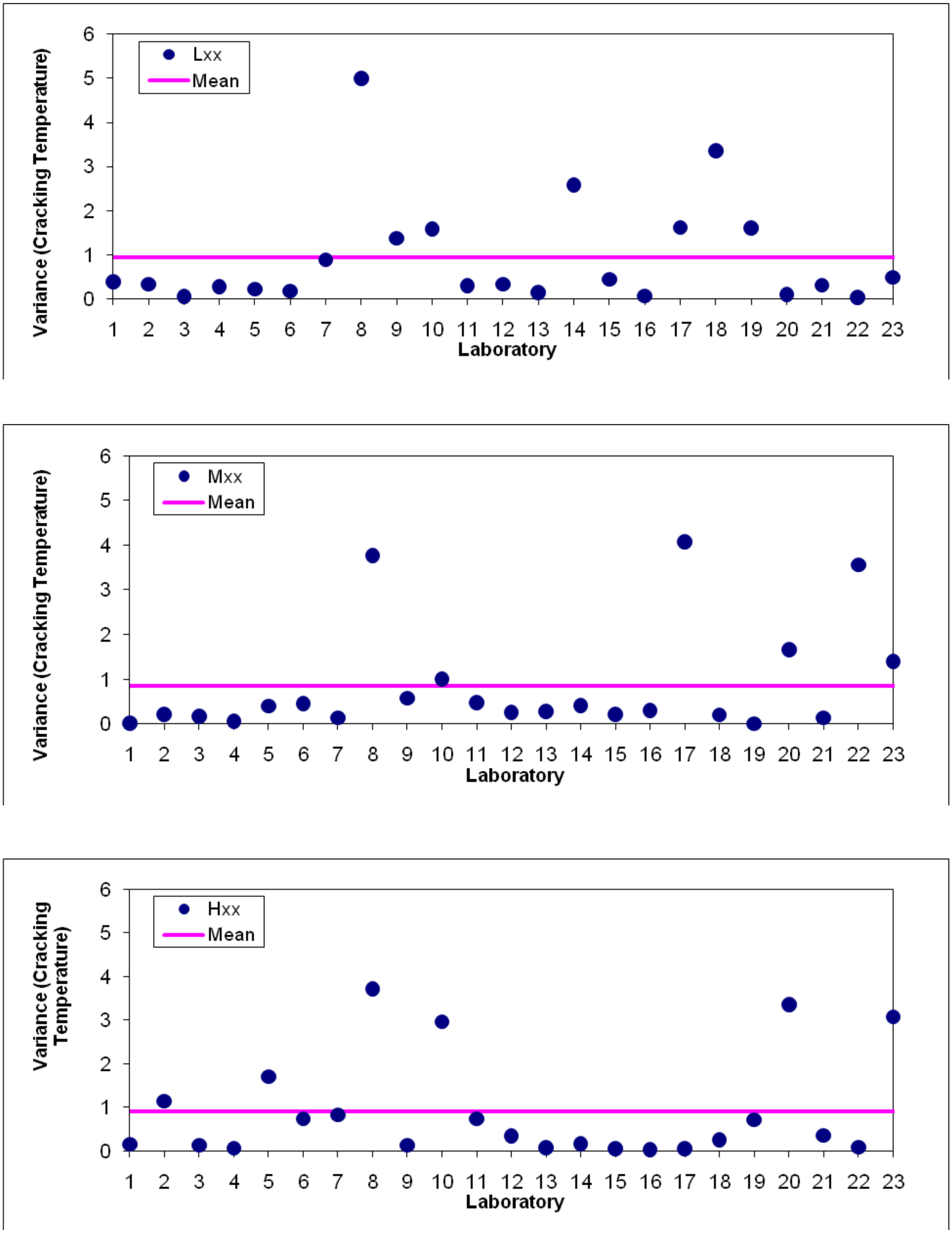

Figure 5. ABCD ILS Results: Within-lab variance of ABCD cracking temperature.

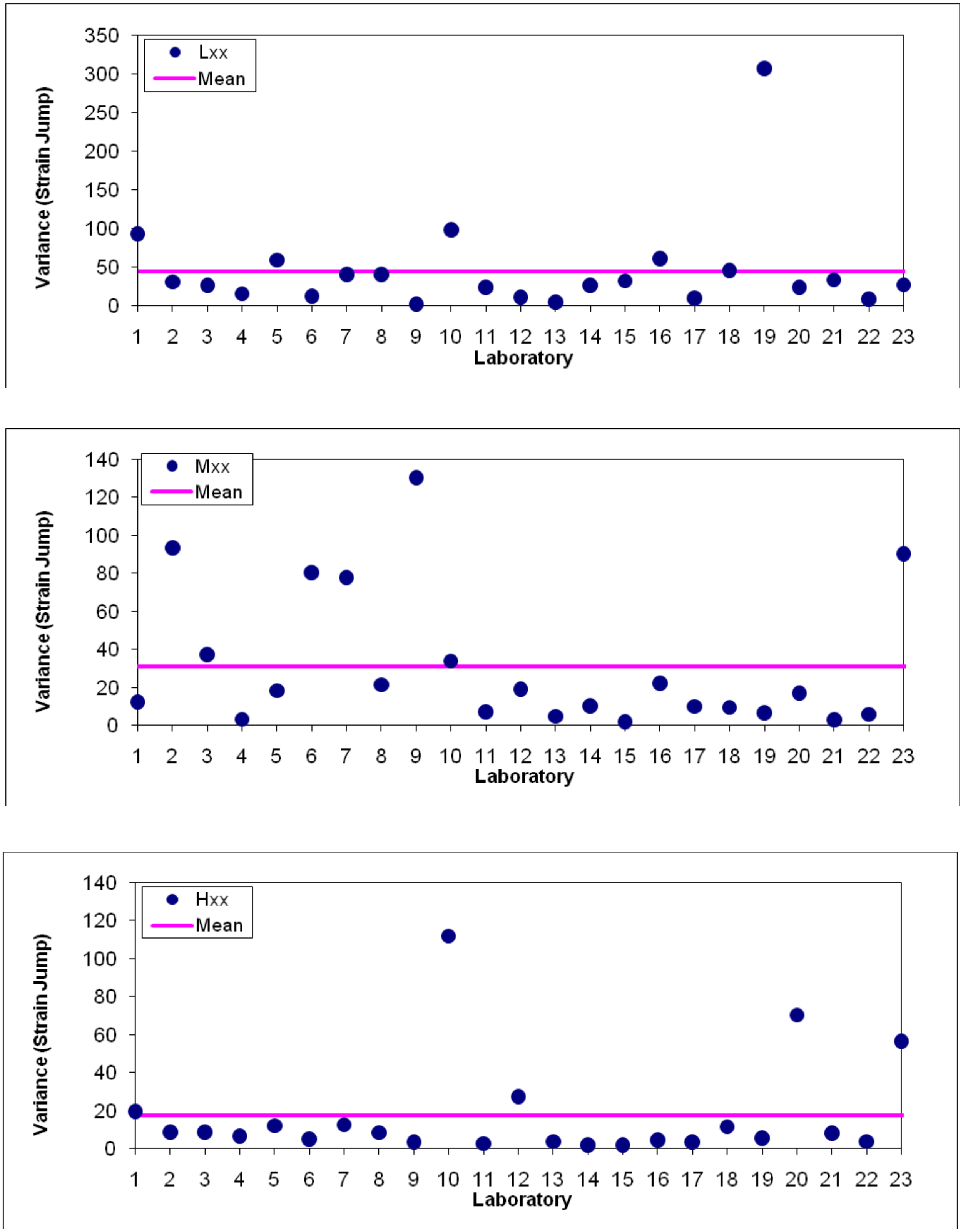

Figure 6. ABCD ILS Results: Within-lab variance of strain jump.

Table 5. Statistical Summary of ABCD ILS Results

	Cracking Temperature (°C)			Strain Jump (με)		
	PG70-28 (Lxx)	**PG76-22 (Mxx)**	**PG88+6 (Hxx)**	**PG70-28 (Lxx)**	**PG76-22 (Mxx)**	**PG88+6 (Hxx)**
Average	-41.5	-40.4	-12.3	41.0	39.6	20.5
Minimum	-44.8	-42.4	-15.8	32.8	21.5	13.1
Maximum	-39.4	-38.4	-7.9	68.0	57.6	37.4
Within-lab variance	0.94	0.86	0.91	45.0	31.1	17.3
Minimum	0.03	0.02	0.05	2.3	1.9	1.9
Maximum	5.00	3.77	3.71	98.4	130.5	112.0
Between-lab variance	1.87	1.19	2.58	62.4	75.1	25.7

Table 6. Precision Estimates for ABCD Test

Condition	**Standard Deviation (1S)**[a]	**Acceptable Range of Two Test Results (D2S)**[a]
Single-operator precision:		
Cracking temperature (°C)	0.95	2.69
Strain jump (με)	5.48	15.50
Facture stress (MPa)	0.86	2.43
Multilaboratory precision:		
Cracking temperature (°C)	1.36	3.85
Strain jump (με)	7.21	20.39
Facture stress (MPa)	1.13	3.20

[a] These values represent the 1S and D2S limits described in ASTM Practice C 670.

CHAPTER 4. BENDING BEAM RHEOMETER CRITICAL TEMPERATURE INTERLABORATORY STUDY

The same three asphalt binders used in ABCD ILS were also used for the BBR Critical Temperature ILS following ASTM C802. For the BBR ILS, one run consisted of two specimens tested at each of two test temperatures (total of four BBR specimens). The averages of two measurements at each of two temperatures were used to find the BBR critical temperature. The BBR critical temperature is the higher temperature of two at which creep stiffness (S) equals 300 MPa (43.51 ksi) and at which m-value equals 0.300. For each binder, the critical temperature measurements were repeated three times (total of 12 BBR specimens per binder). Typically, BBR critical temperature is determined by performing BBR at two temperatures where resulting creep stiffness and m-values bracket the specification limit values (300 MPa [43.51 ksi] stiffness and 0.300 m-value). However, as shown in table 7, none of the S and m-values bracketed the current AASHTO specification limit values. Determination of the BBR critical temperature for 300 MPa (43.51 ksi) stiffness and 0.300 m-value using these data would require an extrapolation process and would result in a larger variability than the interpolation process typically used in the current grading practice. To make determination of BBR critical temperature an interpolation process, arbitrary limit values bracketed by the results at two adjacent test temperatures were chosen for each binder. For BBR critical temperature for stiffness, 100 MPa (14.5 ksi), 100 MPa, and 200 (29.01 ksi) MPa were chosen for the low-, medium-, and high-stiffness binders, respectively. With these limit values, the determination of BBR critical temperature became an interpolating operation. For BBR critical temperature for m-value, 0.500, 0.400, and 0.400 were chosen for the low-, medium-, and high-stiffness binders, respectively, for the same reason. As mentioned earlier, for limit values of 300 MPa (43.51 ksi) creep stiffness and 0.300 m-value, determination of BBR critical temperature required an extrapolating operation. The results of the BBR ILS, including the averages and standard deviations of extrapolated and interpolated critical temperatures, are summarized in tables 7 and 8.

The coefficients of variation (CVs) of the BBR creep stiffness and slope (m-value) are summarized in table 9 and compared with the values given in AASHTO T313. For the BBR ILS data, CVs of the creep stiffness and slope for single-operator measurement were similar to the values given in AASHTO T313. For multilaboratory measurement, CVs for the low- and medium-stiffness binders were significantly smaller than the values given in AASHTO T313. The very high CVs for the high-stiffness binder were probably due to the unusually high stiffness, which made the BBR sample preparation difficult. The high-stiffness binder was not a typical paving-grade asphalt binder, and none of the ILS laboratories would have had sufficient experience testing such a binder with the BBR test. Overall, it can be concluded that the ILS BBR data were valid and could be used to determine the precision estimates of the BBR critical temperature in comparison with the precision estimates for the ABCD cracking temperature.

A statistical summary of BBR critical temperature ILS results is presented in table 10, and the precision estimates of the test are given in table 11. While the BBR critical temperatures at

300 MPa (43.51 ksi) creep stiffness and 0.300 m-value were much warmer than the ABCD cracking temperatures, the relative ranks of the binders from both tests were the same. For the low- and medium-stiffness binders, when interpolated, the within-lab and the between-lab variances were very low (s^2 = 0.06–0.23 ºC^2). The variances for the high-stiffness binder were significantly larger (s^2 = 0.45 and 1.38 ºC^2), probably due to the difficulty experienced in trimming the stiff samples.

As expected, a better precision was resulted for an interpolating condition where the specification limit values were bracketed by two test values obtained from BBR tests performed at two adjacent grading temperatures. When a single operator runs the BBR critical temperature determination twice on the same sample, the acceptable range of two test results should be less than 1.9 °C (3.4 °F) and 1.2 °C (2.2 °F) for extrapolating and interpolating conditions, respectively. When two different operators at two different laboratories perform the BBR critical temperature determination on the same sample, the acceptable range of two test results should be less than 3.5 °C (6.3 °F) and 2.1 °C (3.8 °F) for extrapolating and interpolating conditions, respectively.

The precision of ABCD cracking temperature was somewhat less than that of the BBR critical temperature. However, it should be pointed out that the real point of thermal cracking is determined by comparing thermal stress and the strength of asphalt binder. Thermal cracking occurs when thermal stress exceeds strength. The BBR critical temperature does not consider strength. If the variability of strength determination were added to BBR variability for real cracking temperature determination, the level of precision would be similar to that of the ABCD. Furthermore, most of the participating laboratories had only about a week of experience with the ABCD test procedure before starting the ILS ABCD tests while they had years of experience with the BBR. As laboratories gain more experience with ABCD testing, the precision of ABCD test results will improve.

Table 7. BBR ILS Results: Average of Three Runs

					Extrapolation	Interpolation	
Lab	**S, -18 °C (MPa)**	**S, -12 °C (MPa)**	**m, -18 °C**	**m, -12 °C**	**Tcr (°C) S = 300 MPa & m = 0.300**	**Tcr (S) (°C) S = 100 MPa**	**Tcr (m) (°C) m = 0.500**
Low-Stiffness Binder (PG 70-28)							
FL DOT	122.7	40.0	0.423	0.521	-25.5	-16.4	-13.3
KS DOT	105.3	38.3[a]	0.417	0.519[a]	-24.3	-17.8	-13.1
MA DOT	117.4	38.8	0.409	0.499	-25.3	-16.7	-11.9
MN DOT	118.7	42.4	0.394	0.479	-24.8	-16.6	-10.5
MT DOT	115.2	39.9	0.411	0.518	-24.2	-16.8	-13.0
NCSC	116.0	30.6	0.404	0.525	-23.2	-16.9	-13.2
NY DOT	107.7	40.2	0.421	0.509	-26.3	-17.3	-12.6
OH DOT	113.3	39.5	0.413	0.506	-25.3	-16.9	-12.4
VT DOT	121.3	41.2	0.404	0.492	-25.0	-16.4	-11.5
TFHRC	128.5	39.7	0.421	0.518	-25.5	-16.1	-13.1
Avg	**116.6**	**39.0**	**0.4117**	**0.5085**	**-24.95**	**-16.78**	**-12.44**
Medium-Stiffness Binder (PG 76-22)							
Lab	**S, -18 °C**	**S, -12 °C**	**m, -18 °C**	**m, -12 °C**	**300 MPa & 0.300**	**S = 100 MPa**	**m = 0.400**
FL DOT	155.8	54.7	0.396	0.491	-24.0	-14.7	-17.7
KS DOT	130.7	46.9	0.391	0.488	-23.6	-15.8	-17.4
MA DOT	145.7	51.8	0.383	0.477	-23.4	-15.1	-16.9
MN DOT	148.5	55.4	0.365	0.468	-21.8	-14.9	-16.0
MT DOT	145.4	52.3	0.386	0.492	-22.9	-15.1	-17.2
NCSC	151.0	51.9	0.385	0.480	-23.3	-14.9	-17.0
NY DOT	139.5	50.8	0.409	0.482	-27.0	-15.3	-18.8
OH DOT	144.2	52.3	0.404	0.488	-25.6	-15.1	-18.4
VT DOT	148.4	56.2	0.392	0.488	-24.1	-14.9	-17.5
TFHRC	153.3	53.9	0.397	0.488	-24.4	-14.8	-17.8
Avg	**146.2**	**52.6**	**0.3908**	**0.4842**	**-24.02**	**-15.06**	**-17.48**
High-Stiffness Binder (PG 88+6)							
Lab	**S, 0 °C**	**S, +6 °C**	**m, 0 °C**	**m, +6 °C**	**300 MPa & 0.300**	**S = 200 MPa**	**m = 0.400**
FL DOT	266.7	108.3	0.354	0.453	-1.3	2.5	2.8
KS DOT	104.5[b]	80.7	0.436[b]	0.463	NA	NA	NA
MA DOT	242.3	98.1	0.345	0.451	-2.3	1.8	3.2
MN DOT	204.3	106.8	0.363	0.449	-4.3	0.0	2.6
MT DOT	276.3	48.0	0.330	0.545	-0.6	2.0	1.9
NCSC	194.0	106.0	0.362	0.445	-4.6	-0.4	2.7
NY DOT	253.7	100.8	0.346	0.452	-1.8	2.1	3.1
OH DOT	279.0	115.9	0.338	0.438	-0.8	2.9	3.7
VT DOT	267.8	112.7	0.338	0.441	-1.3	2.6	3.6
TFHRC	260.5	--[c]	0.346	--[c]	NA	NA	NA
Avg	**234.9**	**97.5**	**0.3558**	**0.4596**	**-2.12**	**1.68**	**2.95**

[a] no replicate; [b] outlier; -- [c] data were not reported; NA = not available

S = creep stiffness; m = slope; Tcr = critical temperature

Table 8. BBR ILS Results: Standard Deviation of Three Runs

Low-Stiffness Binder (PG 70-28)							
Lab	S, -18°C (MPa)	S, -12°C (MPa)	m, -18°C	m, -12°C	Extrapolation	Interpolation	
					Tcr (°C)	Tcr (S) (°C)	Tcr (m) (°C)
FL DOT	1.0	1.2	0.0012	0.0021	0.19	0.07	0.11
KS DOT	2.9	--[a]	0.0045	--[a]	NA	NA	NA
MA DOT	2.3	2.3	0.0041	0.0035	0.60	0.13	0.23
MN DOT	7.9	3.1	0.0055	0.0053	1.09	0.50	0.53
MT DOT	0.3	0.7	0.0012	0.0039	0.36	0.02	0.17
NCSC	3.9	3.0	0.0036	0.0153	0.47	0.26	0.67
NY DOT	3.0	0.3	0.0025	0.0061	0.66	0.24	0.39
OH DOT	1.3	1.1	0.0021	0.0033	0.18	0.10	0.21
VT DOT	5.5	0.8	0.0037	0.0021	0.39	0.28	0.13
TFHRC	4.0	0.5	0.0059	0.0063	0.36	0.20	0.39
Avg	3.2	1.5	0.0034	0.0053	0.48	0.20	0.31
Medium-Stiffness Binder (PG 76-22)							
Lab	S, -18°C (MPa)	S, -12°C (MPa)	m, -18°C	m, -12°C	Extrapolation	Interpolation	
					Tcr (°C)	Tcr (S) (°C)	Tcr (m) (°C)
FL DOT	0.8	0.3	0.0010	0.0038	0.18	0.02	0.07
KS DOT	9.6	1.6	0.0020	0.0062	0.13	0.48	0.15
MA DOT	6.9	2.3	0.0057	0.0034	0.88	0.17	0.28
MN DOT	14.8	3.1	0.0035	0.0053	0.40	0.53	0.16
MT DOT	2.4	3.3	0.0086	0.0028	0.76	0.13	0.44
NCSC	4.0	0.6	0.0057	0.0048	0.67	0.10	0.30
NY DOT	4.9	0.3	0.0035	0.0013	0.91	0.19	0.35
OH DOT	2.5	1.9	0.0123	0.0033	1.78	0.10	0.98
VT DOT	3.1	1.1	0.0030	0.0299	1.62	0.13	0.28
TFHRC	3.8	1.3	0.0013	0.0025	0.18	0.10	0.08
Avg	5.3	1.6	0.0046	0.0063	0.75	0.19	0.31
High-Stiffness-Binder (PG 88+6)							
Lab	S, 0°C (MPa)	S, +6°C (MPa)	m, 0°C	m, +6°C	Extrapolation	Interpolation	
					Tcr (°C)	Tcr (S) (°C)	Tcr (m) (°C)
FL DOT	2.8	2.5	0.0028	0.0003	0.13	0.07	0.10
KS DOT	15.6	8.9	0.0031	0.0152	NA	NA	NA
MA DOT	7.7	2.1	0.0057	0.0116	0.43	0.25	0.22
MN DOT	25.7	2.5	0.0003	0.0042	0.31	1.82	0.12
MT DOT	4.6	3.5	0.0041	0.0068	0.11	0.08	0.08
NCSC	4.1	3.5	0.0080	0.0015	0.94	0.29	0.37
NY DOT	7.5	2.6	0.0043	0.0008	0.40	0.18	0.14
OH DOT	1.3	1.8	0.0010	0.0018	0.05	0.05	0.06
VT DOT	12.3	3.1	0.0033	0.0034	0.56	0.32	0.17
TFHRC	5.6	--[b]	0.0028	--[b]	NA	NA	NA
Avg	8.7	3.4	0.0035	0.0050	0.36	0.38	0.16

[a] no replicate; -- [b] data were not reported; NA = not available

S = creep stiffness; m = slope; Tcr = critical temperature

Table 9. Coefficient of Variation of BBR Creep Stiffness and Slope

	Coefficient of Variation (%)			
	Single Operator		Multilaboratory	
Binder Type and Test Temperature	Creep Stiffness	m-value	Creep Stiffness	m-value
PG 70-28 @ 0 °C	3.3	0.9	5.6	2.2
PG 70-28 @ 6 °C	4.5	1.3	7.8	2.8
PG 76-22 @ -18 °C	4.5	1.5	4.2	3.0
PG 76-22 @ -12 °C	3.6	2.1	4.6	0.9
PG 88+6 @ -18 °C	5.0	1.2	24.2	8.8
PG 88+6 @ -12 °C	4.1	1.5	21.6	7.1
Average	4.2	1.4	5.6[a]	2.2[a]
AASHTO T313	3.2	1.4	9.5	4.6

[a] Average excluding PG 88+6 data

Table 10. Statistical Summary of BBR Critical Temperature ILS Results

	Extrapolation (S = 300 MPa and m-value = 0.300)			Interpolation Based on Creep Stiffness		
	PG 70-22	PG 76-28	PG 88+6	PG 70-22	PG 76-22	PG 88+6
Average	-25.0	-24.0	-2.1	-16.8	-15.1	1.7
Minimum	-26.3	-27.0	-4.6	-17.8	-15.8	-0.4
Maximum	-23.2	-21.8	-0.6	-16.1	-14.7	2.9
Within-lab variance	0.30	0.87	0.21	0.06	0.06	0.45
Between-lab variance	0.62	1.78	2.29	0.23	0.09	1.38

Table 11. Precision Estimates for BBR Critical Temperature

	Standard Deviation (1S)[a]		Acceptable Range of Two Test Results (D2S)[a]	
Condition	Extrapolated	Interpolated	Extrapolated	Interpolated
Single-operator precision:				
Critical temperature (°C)	0.68	0.44	1.9	1.2
Multilaboratory precision:				
Critical temperature (°C)	1.25	0.75	3.5	2.1

[a] These values represent the 1S and D2S limits described in ASTM Practice C 670.

CHAPTER 5. NO-TRIM ABCD EXPERIMENT

As an attempt to improve precision of ABCD testing, a no-trim ABCD test procedure was developed. The test procedure used in the ABCD ILS consists of seven simple steps:

1. Lubricating the ABCD rings and silicone rubber molds.
2. Pouring the sample into the ABCD ring-mold assemblies.
3. Trimming excess asphalt on the ABCD ring-mold assemblies.
4. Twisting the ABCD rings to break the bond at the binder/ABCD ring interface.
5. Connecting the ABCD rings to a data acquisition system.
6. Starting the ABCD test software and completing the test.
7. Cleaning the ABCD rings and the silicone molds.

The only step that requires some degree of skill to obtain high-quality data is the trimming process. Trimming disturbs the specimen and if done carelessly may pull asphalt binder off of the ABCD ring surface; pull the asphalt binder upward, causing excessive trimming; and damage the silicone rubber mold.

No-Trim ABCD tests were performed by pouring the exact volume of asphalt binder to form the test specimen. The exact volume of an ABCD specimen is 14.38 cm^3 (0.88 in^3), the target volume of asphalt binder at 25 °C (77 °F). When the 200 $\mu\varepsilon$/°C CTE is assumed, the volume of asphalt binder at 170 °C (338 °F) pouring temperature becomes 15.63 cm^3 (0.95 in^3). For the No-Trim ABCD experiments, the depth of annulus space between the silicone rubber mold and the ABCD ring was increased from 12.7 mm (0.50 in.) to 13.71 mm (0.54 in.) to accommodate the expanded volume of asphalt binder at the pouring temperature. Several designs of pouring device were tried with varying levels of success. Due to the high viscosity of asphalt binder, any pouring device relying on gravitational force could not control volume accurately and efficiently. A precision-made, syringe-type, pouring device is needed and under development.

The No-Trim ABCD experiment proceeded without the syringe-type pouring device. Instead, it was decided to control the mass of asphalt binder. The specific gravity of asphalt binder was assumed as a value between 1.01 and 1.03. Then, the mass of asphalt binder occupying 14.38 cm^3 (0.88 in^3) volume would range from 14.5 g to 14.8 g (from 0.51 oz to 0.52 oz). The mass of trimmed asphalt specimens for ABCD testing was about 14.0 g, significantly less than the theoretical 14.5–14.8 g (0.51–0.52 oz) due to the demolding agent (glycerin-talc mixture) and possible over-trimming. Different operators would use different amounts of demolding agent, resulting in different amounts of asphalt binder being used to form the ABCD test specimens. These differences could also contribute to the variability of ABCD test results. In the No-Trim ABCD experiment, the ABCD ring and mold assembly was placed on an electrical balance and the heated asphalt binder was carefully poured while the mass of the sample was closely monitored. The target mass for the No-Trim experiment was between 14 g and 16 g (0.49 oz and 0.56 oz). A few samples were intentionally prepared with 7–8 g (0.25–0.28 oz) or 16–17 g (0.56–0.60 oz) of asphalt binder. When the binder sample was poured while it was sufficiently warm, the top surface of the resulting ABCD specimen was always clean and uniform. Post-test visual inspection of the ABCD specimen also showed that the test specimens did not contain entrapped air bubbles or cold joints if they were prepared with sufficiently warm asphalt binder.

Three asphalt binders (unaged AAA-1, unaged AAB-1, and unaged AAF-1) used in this No-Trim experiment had been previously tested following the current trimming procedure for 20, 5, and 8 times, respectively. Their masses were not determined in the trimmed tests. In addition to the Trim versus No-Trim comparison, the effects of the ring type (open versus covered), rotation (rotation versus no rotation), and mold lubrication (lubed mold versus not-lubed mold) on ABCD test results were also determined.

The current ABCD ring has a bottom and a top plastic cover protecting the inside sensors and allowing easy handling. However, the covers influence the strain readings during the ABCD tests due to greatly different CTEs between the plastic covers and the ABCD rings. This cover–ring interaction seemed to cause the relatively large variability of the strain-jump magnitude.

"Rotation" refers to twisting the ABCD ring before the start of the test to break bonds between the ABCD ring and the asphalt binder specimen. To avoid causing unwanted specimen deformation, the rotation is usually done after about an hour, when the test specimen is sufficiently cooled. If the rotation is not needed in the No-Trim ABCD test, the binder specimens can be tested right after pouring without waiting an hour, thus saving time.

In the current test procedure, the ABCD mold is lubricated with a glycerin-talc mixture before the binder sample is poured. However, as pointed out earlier, the mold lubrication might be a variable affecting ABCD test results by displacing different amounts of the asphalt binder forming the ABCD test specimen. The trimming also leaves smeared asphalt binder on the top surface of the mold, and cleaning with soap water is always necessary. If the lubrication is not needed, cleaning the silicone rubber molds after the test may not be needed. The elimination of lubrication saves testing time and potentially improves the precision of ABCD test by improving control of the volume of asphalt binder specimen.

A total of 111 specimens were tested following the No-Trim ABCD test procedure; the results are presented in the appendix and plotted in figures 7–9. For unaged AAA-1 binder with a specimen mass between 13.5 g and 16 g (0.48–0.56 oz), the range of No-Trim ABCD cracking temperature was almost identical to the range of 20 trimmed ABCD data previously obtained following the current test procedure. No-Trim data were obtained from tests performed with various procedures that included variations in rotation, ring type, and lubrication of mold. A similar trend was also observed for unaged AAB-1 and unaged AAF-1 binders. The ranges of both trimmed and No-Trim ABCD cracking temperatures were about 4 °C (7 °F), except for the trimmed cracking temperature for unaged AAB-1, probably due to the small number of data. For statistical analysis, 10 data obtained from specimens with less than 13 g (0.46 oz) or more than 16 g (0.56) mass were excluded. The similarity of the ABCD cracking temperatures of trimmed and No-Trim samples of unaged AAA-1 is also shown in table 12. Their means and standard deviations are very similar.

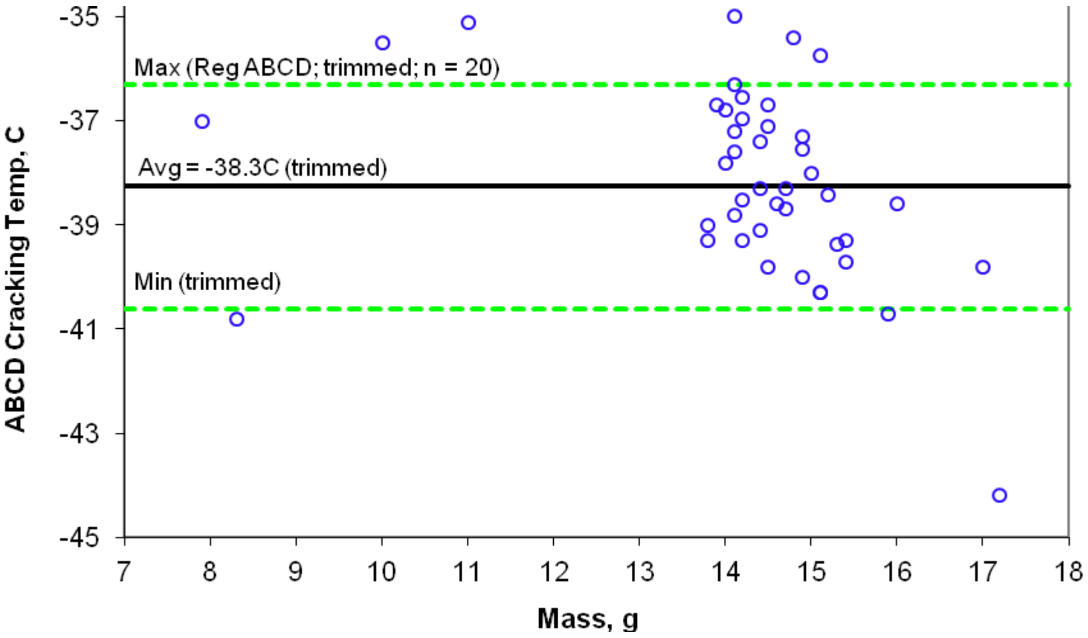

Figure 7. Cracking temperature of Unaged AAA-1 using No-Trim ABCD Test.

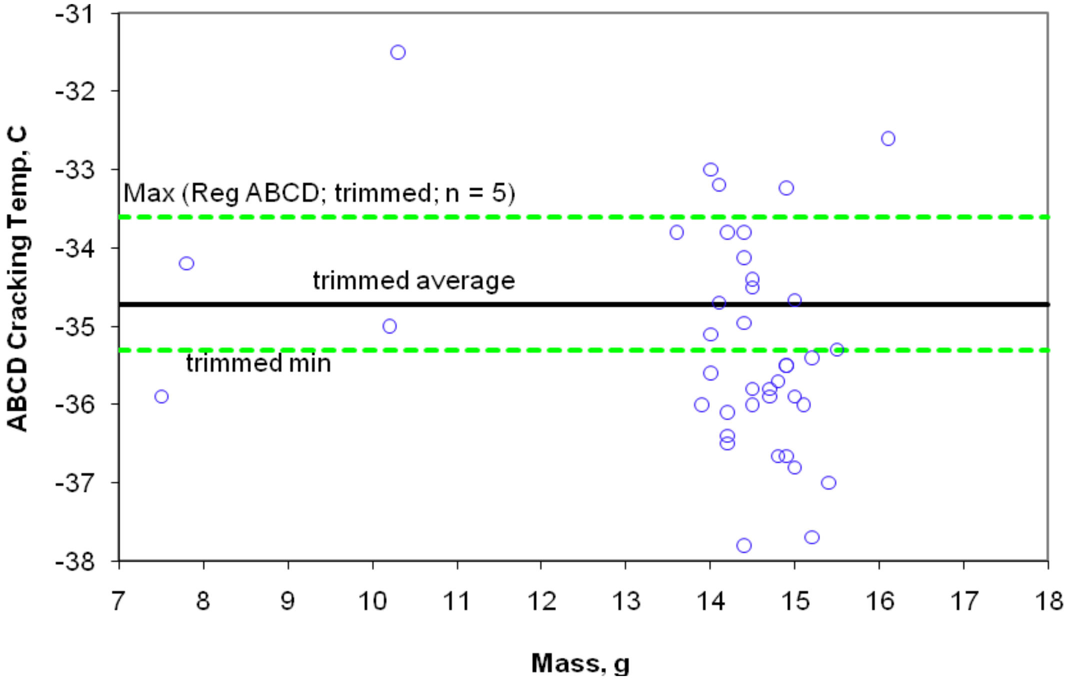

Figure 8. Cracking temperature of unaged AAB-1 using No-Trim ABCD Test.

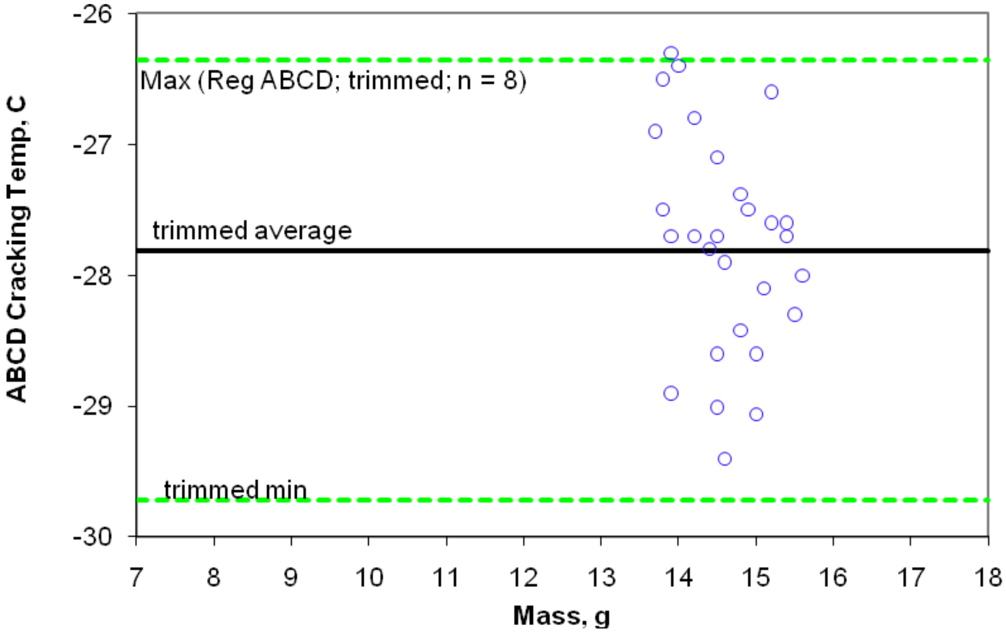

Figure 9. Cracking temperature of unaged AAF-1 using No-Trim ABCD Test.

Table 12. Descriptive Statistics of Trimmed and No-Trim ABCD Cracking Temperature of AAA-1 Binder

Trim	N	Mean	Standard Deviation	Standard Error Mean
No-Trim	37	-38.12 °C	1.43 °C	0.23
Trimmed	20	-38.25 °C	1.37 °C	0.31

Regression analyses were performed to identify factors significantly affecting the ABCD cracking temperature (table 13) and strain jump (table 14). For the 5 percent significance level (p-value < 0.05), the effects of rotation, ring type, and mold lubrication on the cracking temperature were not significant. The only significant factor was the mass of sample. If the mass of sample increases by 1.0 g (0.04 oz), the cracking temperature would decrease by 0.62 °C (1.12 °F). For the strain jump, the ring type, mold lubrication, and sample mass did not have a significant effect. The only significant factor affecting the strain jump was rotation of the ABCD ring. The ABCD test with ring rotation would reduce the strain jump by 7.6 με, probably due to reduced adhesion between the ABCD ring and the binder sample. When the No-Trim data were separately analyzed, the standard deviation of ABCD strain jump was 10.84 με for tests without rotation and 4.40 με for tests with rotation. Rotation of the ABCD ring significantly reduced the variability of the strain jump and was an essential step to be kept in the ABCD test procedure.

Table 13. Regression Analysis: Factors Affecting ABCD Cracking Temperature

	Analysis of Variance				
	Sum of Squares	df	Mean Square	F	p-value
Regression	1798.099	6	299.683	213.71	0.000
Residual	131.813	94	1.402		
Total	1929.912	100			
R Square = 0.932; Standard Error of the Estimate = 1.18 °C					

	Regression Coefficient		
	Coefficients	t	p-value
(Constant)	-29.258	-8.903	0.000
AAB-1	2.800	10.094	0.000
AAF-1	10.450	34.741	0.000
Rotation	0.254	0.901	0.370
Ring Type	0.406	1.721	0.089
Mold Lube	-0.282	-0.926	0.357
Mass	-0.620	-2.820	0.006

Table 14. Regression Analysis: Factors Affecting Strain Jump

	Analysis of Variance				
	Sum of Squares	df	Mean Square	F	p-value
Regression	1712.817	6	285.469	3.986	0.001
Residual	6732.168	94	71.619		
Total	8444.985	100			
R Square = 0.203; Standard Error of the Estimate = 8.46 με					

	Regression Coefficient		
	Coefficients	t	p-value
(Constant)	30.024	1.278	0.204
AAB-1	-2.966	-1.496	0.138
AAF-1	-5.065	-2.356	0.021
Rotation	-7.645	-3.801	0.000
Ring Type	-2.667	-1.580	0.118
Mold Lube	-1.474	-0.677	0.500
Mass	0.385	0.245	0.807

Based on this experiment, a revised ABCD test procedure is recommended, which has two major changes from the current version:

1. The specimen trimming step is eliminated. Instead, the exact volume (14.38 cm^3 [0.88 in^3] at 25 °C [77 °F] or 15.63 cm^3 [0.95 in^3] at the pouring temperature) of binder sample is poured.
2. The silicone rubber mold is not lubricated with glycerin-talc mixture. The surface of the ABCD ring is still lubricated to facilitate the rotation of the ring prior to the test.

The elimination of the mold lubrication and trimming steps also eliminated the need for cleaning the silicone mold with soap and water. As shown in figure 10, the silicone molds remained very clean after the test and were immediately ready for the next test without the cleaning step.

Among the No-Trim data, there were 14 results from tests following the revised test procedure with covered ABCD rings (excluding data from no rotation, lubrication of mold, and open ring). For these data, the standard deviations (pooled among three binder types) for the cracking temperature and the strain jump were 0.96 °C (1.73 °F) and 3.52 με (or 0.55 MPa [79.8 psi] for fracture strength), respectively. To compare the standard deviations obtained from the ABCD ILS in table 6 (the current procedure), the single-operator precision for the cracking temperature of the revised procedure would be about the same (0.96 °C versus 0.95 °C [1.73 °F versus 1.71 °F]), and the precision for the strain jump would be improved (3.52 με versus 5.48 με). For the multilaboratory testing of the revised procedure, precision of both the cracking temperature and the strain jump would be improved greatly from 1.36 °C (2.45 °F) and 7.21 με (shown in table 6) to close to 0.96 °C (1.73 °F) and 3.52 με because of the simplified test procedure and the elimination of a couple of steps that required careful execution by operators. The average and the standard deviation of No-Trim sample mass were 14.56 g (0.51 oz) and 0.35 g (0.01 oz), respectively. With a proper pouring device, the standard deviation of the sample mass can be reduced significantly and the precision of the ABCD test may be further improved for both single-operator and multilaboratory testing.

Figure 10. ABCD silicone molds and rings after No-Trim ABCD test.

CHAPTER 6. SUMMARY

For the ABCD ILS, data from 23 laboratories were used. With very limited experience with the ABCD equipment and test procedure, all participating laboratories were able to complete the ABCD ILS without major difficulty. Ten laboratories also provided data for the BBR Critical Temperature ILS.

The precision estimates for the ABCD test and the BBR critical temperature were determined and are presented in tables 6 and 11, respectively. The standard deviations of the ABCD cracking temperature, strain jump, and fracture strength for the single-operator ABCD tests were 0.95 °C (1.71 °F), 5.48 με, and 0.86 MPa (125 psi), respectively. The standard deviations of the ABCD cracking temperature, strain jump, and fracture strength for the multilaboratory ABCD tests were 1.36 °C (2.45 °F), 7.21 με, and 1.13 MPa (163.9 psi), respectively. The standard deviations of the BBR critical temperature for single-operator and multilaboratory testing were 0.44 °C (0.79 °F) and 0.75 °C (1.35 °F), respectively, when the critical temperatures were determined by interpolation. When extrapolation was used, the standard deviations of the BBR critical temperature for single-operator and multilaboratory tests were 0.68 °C (1.22 °F) and 1.25 °C (2.25 °F), respectively. Interpolation is the common case in BBR testing where the test results from two adjacent grading temperatures bracket the specification limit values (300 MPa [43.51 ksi] creep stiffness and 0.300 m-value). Extrapolation is the case where the BBR test results from two adjacent grading temperatures do not bracket the limit values. The BBR critical temperature precision is better than the ABCD cracking temperature precision. However, it should be pointed out that the BBR critical temperature alone cannot estimate the proper cracking temperature of asphalt binder. A strength test must be performed and combined with the BBR test results. Then, the precision of the resulting cracking temperature by BBR would be similar to that of ABCD cracking temperature.

The No-Trim ABCD experiment, performed with a limited number of binders, showed that the trimming and lubrication of the silicone mold in the current ABCD procedure can be eliminated. Based on these finding, a revised ABCD test procedure was developed that did not have steps for trimming the sample and lubricating the silicone mold. The results of the revised ABCD test procedure would have the same precision level for the ABCD cracking temperature and would improve the precision of the strain jump for the single-operator test. Multilaboratory precision of the ABCD cracking temperature and the strain jump would be significantly improved with the revised ABCD test procedure.

CHAPTER 7. FUTURE PLANS

ABCD is an empirical test method evaluating the low-temperature performance of asphalt binder. The ABCD test method is simple and practical for estimating the cracking temperature of asphalt binder because it tests the samples under a field-like condition, eliminating the need for assuming and measuring several asphalt binder properties required in the theoretical calculation procedure.

The ABCD test method has been adopted as an AASHTO Provisional Standard. Provisional Standards are adopted as standards on a temporary basis for a maximum of 8 years and are reviewed every 2 years. At any time during the 8-year period, AASHTO can convert a Provisional Standard into a Full Standard. The ABCD is not intended to replace the current low-temperature binder grading specifications and test methods. Instead, the ABCD test method may be added to the currently available test methods for characterizing and grading asphalt binders at low temperatures.

Following are recommendations for the implementation of ABCD for prediction of low-temperature performance of asphalt binders.

- The relationship between the ABCD cracking temperatures of asphalt binders and the field performance of asphalt pavements should be determined for utilization of ABCD test results in the current asphalt binder low-temperature grading specifications. Though the properties of asphalt binder have the major influence, other variables, such as aggregate properties, mixture volumetrics, and pavement structure, also influence the low-temperature performance of asphalt pavement. A future study is needed to determine the ABCD cracking temperature and pavement low-temperature performance while controlling the effects of the aforementioned other pavement variables using laboratory and field samples with known performance data.

- The effects of isothermal conditioning (known as physical hardening) on the low-temperature performance of asphalt binders should be studied with the ABCD. The significant adverse effects of isothermal conditioning of certain asphalt binders on rheological properties(7, 8) and pavement performance(7) at low temperatures have been reported. However, when measured with the ABCD where the contraction of the test specimen was restrained during conditioning, the effects of isothermal conditioning on the ABCD cracking temperature were either adverse or beneficial depending on the asphalt binder type in the limited Phase 1 experiment.(5) A more comprehensive isothermal conditioning study using various binder types and asphalt mixes is needed.

APPENDIX

Results of No-Trim ABCD Tests

Table A-1. Results of No-Trim ABCD Tests

Binder	Trim	Rotation	Ring Type	Mold Lube	Mass, g	Tcr, °C	Jump, με
AAA-1	No	No	Open	Yes	13.8	-39.3	62.6
AAA-1	No	No	Open	Yes	14.1	-38.8	51.5
AAA-1	No	No	Open	Yes	14.5	-37.1	26.3
AAA-1	No	No	Open	Yes	14.6	-38.6	23.0
AAA-1	No	No	Open	Yes	15.9	-40.7	41.2
AAA-1	No	No	Open	Yes	17.0	-39.8	42.2
AAA-1	No	No	Open	Yes	8.3	-40.8	29.9
AAA-1	No	No	Open	Yes	10.0	-35.5	12.5
AAA-1	No	No	Cover	Yes	13.8	-39.0	55.2
AAA-1	No	No	Cover	Yes	14.5	-39.8	23.4
AAA-1	No	No	Cover	Yes	14.9	-40.0	26.1
AAA-1	No	No	Cover	Yes	16.0	-38.6	36.7
AAA-1	No	No	Cover	Yes	17.2	-44.2	22.2
AAA-1	No	No	Cover	Yes	7.9	-37.0	7.0
AAA-1	No	No	Cover	Yes	11.0	-35.1	8.1
AAA-1	No	No	Cover	Yes	15.1	-40.3	39.6
AAA-1	No	No	Cover	Yes	15.1	-40.3	29.2
AAA-1	No	No	Cover	Yes	15.4	-39.7	47.7
AAA-1	No	No	Cover	Yes	15.4	-39.3	27.4
AAA-1	No	Yes	Open	No	14.7	-38.3	29.9
AAA-1	No	Yes	Open	No	14.2	-36.5	29.6
AAA-1	No	Yes	Open	No	14.2	-38.5	25.7
AAA-1	No	Yes	Open	No	14.1	-37.6	24.3
AAA-1	No	Yes	Open	No	15.2	-38.4	28.0
AAA-1	No	Yes	Open	No	15.3	-39.4	28.8
AAA-1	No	Yes	Open	Yes	14.0	-37.8	18.8
AAA-1	No	Yes	Open	Yes	14.1	-37.2	17.5
AAA-1	No	Yes	Open	Yes	14.4	-37.4	22.4
AAA-1	No	Yes	Open	Yes	14.4	-39.1	26.5
AAA-1	No	Yes	Open	Yes	14.7	-38.7	31.7
AAA-1	No	Yes	Open	Yes	14.9	-37.3	20.6
AAA-1	No	Yes	Cover	No	14.5	-36.7	18.5
AAA-1	No	Yes	Cover	No	14.2	-37.0	21.5
AAA-1	No	Yes	Cover	No	14.1	-35.0	15.8
AAA-1	No	Yes	Cover	No	14.1	-36.3	19.6
AAA-1	No	Yes	Cover	No	14.9	-37.5	22.6
AAA-1	No	Yes	Cover	No	15.1	-35.7	22.1
AAA-1	No	Yes	Cover	Yes	13.9	-36.7	18.9
AAA-1	No	Yes	Cover	Yes	14.0	-36.8	15.5
AAA-1	No	Yes	Cover	Yes	14.2	-39.3	29.3
AAA-1	No	Yes	Cover	Yes	14.4	-38.3	28.8
AAA-1	No	Yes	Cover	Yes	14.8	-35.4	13.2
AAA-1	No	Yes	Cover	Yes	15.0	-38.0	25.9
AAB-1	No	No	Open	Yes	13.6	-33.8	19.0

continued next page

Table A-1 continued

Binder	Trim	Rotation	Ring Type	Mold Lube	Mass, g	Tcr, °C	Jump, με
AAB-1	No	No	Open	Yes	13.9	-36.0	47.1
AAB-1	No	No	Open	Yes	14.0	-35.1	23.5
AAB-1	No	No	Open	Yes	14.7	-35.9	47.0
AAB-1	No	No	Open	Yes	15.2	-37.7	27.3
AAB-1	No	No	Open	Yes	16.1	-32.6	16.7
AAB-1	No	No	Open	Yes	7.8	-34.2	10.8
AAB-1	No	No	Open	Yes	10.2	-35.0	41.9
AAB-1	No	No	Cover	Yes	14.1	-34.7	22.2
AAB-1	No	No	Cover	Yes	14.2	-36.1	21.8
AAB-1	No	No	Cover	Yes	14.2	-33.8	22.0
AAB-1	No	No	Cover	Yes	14.8	-35.7	25.8
AAB-1	No	No	Cover	Yes	15.1	-36.0	8.1
AAB-1	No	No	Cover	Yes	15.5	-35.3	27.1
AAB-1	No	No	Cover	Yes	7.5	-35.9	8.0
AAB-1	No	No	Cover	Yes	10.3	-31.5	6.5
AAB-1	No	Yes	Open	No	14.9	-36.7	25.5
AAB-1	No	Yes	Open	No	14.9	-35.5	25.6
AAB-1	No	Yes	Open	No	14.4	-37.8	27.9
AAB-1	No	Yes	Open	No	15.4	-37.0	30.4
AAB-1	No	Yes	Open	No	14.4	-35.0	24.3
AAB-1	No	Yes	Open	No	14.8	-36.7	32.5
AAB-1	No	Yes	Open	Yes	14.2	-36.4	12.9
AAB-1	No	Yes	Open	Yes	14.0	-33.0	12.5
AAB-1	No	Yes	Open	Yes	14.5	-35.8	27.0
AAB-1	No	Yes	Open	Yes	14.4	-33.8	25.8
AAB-1	No	Yes	Open	Yes	15.2	-35.4	22.1
AAB-1	No	Yes	Open	Yes	15.0	-36.8	38.9
AAB-1	No	Yes	Cover	No	15.0	-34.7	20.2
AAB-1	No	Yes	Cover	No	14.9	-33.2	18.1
AAB-1	No	Yes	Cover	No	14.5	-34.4	24.1
AAB-1	No	Yes	Cover	No	14.5	-36.0	30.1
AAB-1	No	Yes	Cover	No	14.1	-33.2	20.3
AAB-1	No	Yes	Cover	No	14.4	-34.1	23.1
AAB-1	No	Yes	Cover	Yes	14.2	-36.5	31.2
AAB-1	No	Yes	Cover	Yes	14.0	-35.6	25.2
AAB-1	No	Yes	Cover	Yes	14.5	-34.5	21.3
AAB-1	No	Yes	Cover	Yes	14.7	-35.8	29.8
AAB-1	No	Yes	Cover	Yes	**15.0**	-35.9	27.5
AAB-1	No	Yes	Cover	Yes	14.9	-35.5	26.0
AAF-1	No	No	Open	Yes	15.6	-28.0	38.6
AAF-1	No	No	Open	Yes	15.1	-28.1	25.1
AAF-1	No	No	Open	Yes	14.2	-26.8	32.9
AAF-1	No	No	Open	Yes	14.5	-27.1	23.7
AAF-1	No	No	Open	Yes	14.0	-26.4	22.6
AAF-1	No	No	Open	Yes	14.2	-27.7	21.5

continued next page

Table A-1 continued

Binder	Trim	Rotation	Ring Type	Mold Lube	Mass, g	Tcr, °C	Jump, με
AAF-1	No	No	Cover	Yes	14.9	-27.5	28.7
AAF-1	No	No	Cover	Yes	15.5	-28.3	40.2
AAF-1	No	No	Cover	Yes	14.5	-28.6	32.3
AAF-1	No	No	Cover	Yes	15.4	-27.6	16.2
AAF-1	No	No	Cover	Yes	13.9	-26.3	17.5
AAF-1	No	No	Cover	Yes	13.8	-26.5	19.4
AAF-1	No	Yes	Open	No	14.5	-29.0	25.8
AAF-1	No	Yes	Open	No	15.0	-29.1	21.2
AAF-1	No	Yes	Open	Yes	15.2	-26.6	12.2
AAF-1	No	Yes	Open	Yes	15.4	-27.7	18.9
AAF-1	No	Yes	Open	Yes	13.9	-28.9	32.1
AAF-1	No	Yes	Open	Yes	13.9	-27.7	18.6
AAF-1	No	Yes	Open	Yes	14.4	-27.8	22.5
AAF-1	No	Yes	Open	Yes	14.6	-29.4	16.0
AAF-1	No	Yes	Cover	No	14.8	-28.4	30.4
AAF-1	No	Yes	Cover	No	14.8	-27.4	25.4
AAF-1	No	Yes	Cover	Yes	15.2	-27.6	13.1
AAF-1	No	Yes	Cover	Yes	15.0	-28.6	19.3
AAF-1	No	Yes	Cover	Yes	13.8	-27.5	21.5
AAF-1	No	Yes	Cover	Yes	13.7	-26.9	18.5
AAF-1	No	Yes	Cover	Yes	14.5	-27.7	20.4
AAF-1	No	Yes	Cover	Yes	14.6	-27.9	26.7

ACKNOWLEDGMENTS

I would like to thank FHWA’s Highways for LIFE Technology Partnership Program and those who volunteered in the interlaboratory study and have helped to bring this study to completion. Special thanks go to FHWA’s Mr. Tom Harman, Ms. Julie Zirlin, Dr. John D’Angelo (now retired), Dr. Jack Youcheff, Dr. Nelson Gibson, and Dr. Audrey Copeland for reviewing the reports and providing valuable technical advices.

I would like to gratefully acknowledge the support from Mr. Ed Morrison of Shelly and Sand, Inc., and Mr. Gaylon Baumgardener of Paragon Technical Service, Inc. in supplying binder samples used in the interlaboratory study.

S-S K.

REFERENCES

1. S. Kim. 2007. "Development of an Asphalt Binder Cracking Device," Final Report for NCHRP Highway IDEA Project 99, Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/archive/studies/idea/finalreports/highway/NCHRP99 Final_Report.pdf

2. S. Kim, Z. Wysong, and J. Kovach. 2006. "Low-Temperature Thermal Cracking of Asphalt Binder by Asphalt Binder Cracking Device," *Transportation Research Record* 1962, pp. 28–35.

3. S. Kim. 2005. "Direct Measurement of Asphalt Binder Thermal Cracking," *ASCE Journal of Materials in Civil Engineering*, vol. 17(6), pp. 632–639.

4. M. G. Bouldin, R. Dongre, G. M. Rowe, M. J. Sharrock, and D. A. Anderson. 2000. "Predicting Thermal Cracking of Pavements From Binder Properties: Theoretical Basis and Field Validation," *Journal of the Association of Asphalt Paving Technologists*, 69, pp. 455–496.

5. S. Kim. 2009. "Asphalt Binder Cracking Device to Reduce Low Temperature Asphalt Pavement Cracking," Final Report Phase I, Highways for LIFE Technology Partnership Program, Award No.: DTFH61-08-G-00005. http://www.fhwa.dot.gov/hfl/partnerships/asphalt/phase1/index.cfm

6. H. Kanerva, T. Vinson, and H. Zeng. 1994. "Low-Temperature Cracking: Field Validation of the Thermal Stress Restrained Specimen Test," SHRP-A-401 Strategic Highway Research Program.

7. P. Yee, B. Aida, S. A. M. Hesp, P. Marks, and K. Tam. 2006. "Analysis of Premature Low-Temperature Cracking in Three Ontario, Canada, Pavements," *Transportation Research Record* 1962, pp. 44–51.

8. D. A. Anderson and M. Marasteanu. (1999). "Physical Hardening of Asphalt Binders Relative to Their Glass Transition Temperatures," *Transportation Research Record* 1661, pp. 27–34.

Highways for LIFE Program Office
Federal Highway Administration
U.S. Department of Transportation
1200 New Jersey Avenue, S.E.
Washington DC 20590

www.fhwa.dot.gov/hfl

JULY 2010
FHWA-HIF-11-029