Phase I Report

January 1, 2008 – December, 2008

Highways for LIFE Technology Partnership Program

Project Title: Asphalt Binder Cracking Device to reduce Low Temperature Asphalt Pavement Cracking

(Award No.: DTFH61-08-G-00005)

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Executive Summary

Phase 1 of "Asphalt Binder Cracking Device (ABCD) to Reduce Low Temperature Pavement Cracking" project consisted of four tasks including refinement of test procedures, field validation of ABCD, refinement of equipment and analysis software, and ruggedness testing. In January 2008, a new testing facility for EZ Asphalt Technology, LLC, was established in Athens, Ohio. The first three tasks utilized 22 asphalt binders.

Regarding refinement of test procedures, ABCD test precision and duration were improved by modifying the silicone mold, improving the trimming process, and determining an optimum cooling rate of 20ºC to 0ºC in the first 30 minutes followed by 0ºC to -60ºC in three hours. ABCD tests of unaged and RTFO/PAV aged SHRP core asphalt binders indicated that, for unaged binders 24 hours of isothermal conditioning at -15ºC caused the ABCD cracking temperatures to rise while, for RTFO/PAV aged binders 24 hour conditioning at -15ºC significantly lowered cracking temperature. To help increase the ease and consistency of ABCD sample preparation, the use of turntables was incorporated. Turntables helped greatly in preventing overfilling and spillage due to misalignment of the pouring stream and the ¼ in. annular gap between the ABCD ring and the mold.

For field validation, binders from National Pooled Fund Study 776, Ohio DOT paving projects, and SHRP binders were tested. There is a moderate relationship between ABCD strain jump and Direct Tension Test (DTT) failure stress for unaged SHRP binders but no statistically significant relationship for PAV aged binders. There is a significant difference in strength measurement between DTT and ABCD as expected since test temperature is fixed in DTT but intentionally not fixed in ABCD test.

Additionally, refinements of equipment and analysis software were conducted. The Free Piston Sterling Cooler prototype environmental chamber was investigated due to its light-weight, quiet, and vibration-free operation. Unfortunately, it was unable to maintain the desired cooling rate of 20ºC per hour, so the Cincinnati Sub-Zero Products cooling chamber will continue to be the mainstay for ABCD testing since it has proven durability and provides consistent cooling rates. Regardless of which chamber is used, if the cooling chamber is opened while still at low temperature, condensation collects on the ring materials sometimes resulting in premature ring and sensor failure. To solve the problem, sensors were coated with water proofing materials. Data collection now runs on both Microsoft Windows XP and Vista, directly controls the temperature in the chamber, and conducts the data analysis

The fourth task was the ruggedness test following ASTM C 1067 – 00. North Central Superpave Center (NC), the University of Wisconsin - Madison (WI), and EZ Asphalt tested RTFO/PAV aged binders (polymer modified and unmodified). Cooling rate, protrusion size, over-trimming, turntable usage, cold joint formation, and conditioning time were studied. Statistical analyses indicated that protrusion size and over-trimming affected cracking temperatures. Additional statistics revealed that the WI lab generally

determined colder cracking temperatures than the other two labs. Supplemental tests at all labs using a modified procedure and improved trimming technique at the WI lab resulted in elimination of laboratory variability from cracking temperature statistics.

As will be further investigated in the Interlaboratory Study in Phase 2, the direct determination of binder cracking temperature and strength, ease of sample preparation and conduction of test, repeatability at other laboratories, and cost-savings to the industry since more reliable results than other methods indicate that the ABCD has much potential to provide a better determination of binder cracking temperature and strength compared to other asphalt binder test devices. In addition to describing details of the four Phase 1 tasks, performance specifications and operating procedures are included in the Appendices in the form of a draft ABCD Standard Test Procedure following AASHTO format and the ABCD User's Guide.

Outline

Acronyms

AASHTO = American Association of State Highway and Transportation Officials
ABCD = Asphalt Binder Cracking Device
ANOVA = Analysis of Variance
AOTR = Agreement Officer's Technical Representative
ASTM = American Society for Testing and Materials
Avg = Average
C = Celsius
CA = California
Diff = Difference
DOT = Department of Transportation
DTT = Direct Tension Test
E_{ABCD} = Young's Modulus of ABCD Ring
A_{ABCD} = Cross-Sectional Area of ABCD Ring
A_{binder} = Cross-Sectional Area of Asphalt Binder
EM = Exxon-Mobil
FHWA = Federal Highway Administration
FPSC = Free Piston Sterling Cooler
F value = Statistical Variable
HfL = Highways for LIFE
hr = Hour
ID = Identification
in. = Inch
kPa = kiloPascal
K = Stress Concentration Factor
LabVIEW = Laboratory Virtual Instrumentation Engineering Workbench (National Instruments, Inc.)
LIFE = Longer-lasting highway infrastructure using Innovations to accomplish the Fast construction of Efficient and safe highways and bridges
LLC = Limited Liability Company
Max = Maximum
Min = Minimum
MN = Minnesota
MPa = Mega Pascal
NC = North Central Superpave Center
ND = Not Determined
NM = Not Measured
NS = Not Significant
NT = Not Tested
OD = Ohio Department (of Transportation)
OH = Ohio
PAV = Pressure Aging Vessel
PG = Performance Grade
PH = Physical Hardening
p-value = Statistical Variable

r^2 = Coefficient of Determination
R^2 = Coefficient of Determination
Rep = Repetition
RMSE = Root Mean Square Error
RTD = Resistance Temperature Detector
RTFO = Rolling Thin Film Oven
SBS = Styrene-Butadiene-Styrene
SD = Standard Deviation
SHRP = Strategic Highway Research Program
StDev = Standard Deviation
T_{cr} = Cracking Temperature
US = United States
W TX = West Texas
WI = Wisconsin
x = x-axis value
WY = Wyoming
y = y-axis value
ε = Strain Jump
σ_f = Fracture Stress
$\mu\varepsilon$ = Microstrain

Introduction

There were four tasks stated in the EZ Asphalt Technology Phase 1 proposal:
Task 1: Refinement of Test Procedures
Task 2: Field Validation of ABCD
Task 3: Refinement of Equipment and Analysis Software
Task 4: Ruggedness Test

The tasks have been completed and are discussed.

In January of 2008, a new testing facility for EZ Asphalt Technology, LLC, was established at the Ohio University Innovation Center. Two technicians were hired and trained to perform ABCD tests and other tasks required for this agreement. For ABCD tests to be performed in Tasks 1, 2, and 3, the following four asphalt binder groups (total of 22 asphalt binders) were used as shown in Tables 1 through 4.

Table 1. SHRP asphalt binders used for ABCD tests.

Sample ID	Grade	
AAA-1	PG 58-28	Lloydminster
AAB-1	PG 58-22	WY Sour
AAC-1	PG 58-16	Redwater
AAD-1	PG 58-28	CA Coast
AAF-1	PG 64-10	W TX Sour
ABM-1	PG 58-10	CA Valley (Replacement for AAG-1)
AAK-1	PG 64-22	Boscan
AAM-1	PG 64-16	W TX Intermediate

Table 2. Asphalt binders from National Pooled Fund Study 776 Phase I used for ABCD tests.

Sample ID	Grade
MN-1	PG 58-40, modifier 1 SBS (Flint Hills)
MN-2	PG 58-34, modifier 1 Elvaloy (Murphy Oil)
MN-3	PG 58-34, modifier 2 SBS (Flint Hills)
MN-4	PG 58-28, plain 1 (Seneca Petroleum)
MN-5	PG 58-28, plain 2 (Payne and Dolan)
MN-6	PG 64-34, modifier 1 Elvaloy (Murphy Oil)
MN-7	PG 64-34, modifier 2 Black Max™ (Husky)
MN-8	PG 64-28, plain 1 (Seneca)
MN-9	PG 64-28, modifier 1 SBS (Seneca Petroleum)
MN-10	PG 64-22, plain (Seneca Petroleum)

Table 3. Asphalt binders from four Ohio 2007 paving projects used for ABCD tests.

Sample ID	Grade
OD1	PG 70-22 SBS
OD2	PG 64-22
OD3	PG 76-22 SBS
OD4	PG 70-22 SBS

Table 4. Asphalt binders from ExxonMobil used for ABCD tests.

Sample ID	Grade
EM1	PG 58-28
EM2	PG 52-34

The binders from the National Pooled Fund Study 776 Phase I were provided by Dr. Mihai Marasteanu of the University of Minnesota and Ohio samples were supplied by Mr. David Powers of Ohio Department of Transportation.

Task 1. Refinement of Test Procedures

The objective of Task 1 was to refine test procedures and equipment to improve the precision of the ABCD test and shorten the test time. Improving the precision of the test was investigated by modifying the silicone sample mold and trimming process. The effect of isothermal conditioning prior to testing was also reviewed in regard to test precision. The shortening of the test time was investigated by increasing the test cooling rate, improving pouring methods and eliminating or simplifying the trimming process.

Through many trials of cooling rates for binders with warm cracking temperatures, it was determined that the optimum cooling profile for the ABCD chamber consists of cooling from 20ºC to 0ºC in 30 minutes followed by cooling from 0ºC to -60ºC at the desired cooling rate.

1A. Cooling Rate

The effect of cooling rate on ABCD cracking temperature was investigated. In investigations prior to Phase 1, only the 10°C/hr rate was used with few exceptions. For the Phase 1 study, four unmodified asphalts (EM1 PAV, EM2 PAV, ABM-1 unaged, and AAM-1 unaged) and two SBS modified binders (OD1 unaged and OD3 unaged) were tested with five different cooling rates (1, 3, 10, 20, and 40ºC/hour). The results are shown in Table 5 and Figure 1. For each sample, quadruplicate samples were tested at each cooling rate except two triplicate sample tests (EM2 @ 20ºC/hr and AAM-1 @1.0ºC/hr).

Table 5. The effects of cooling rate on ABCD cracking temperature (T_{cr}) and standard deviation.

Cool Rate ºC/hr	EM1 PAV		EM2 PAV		ABM-1 Unaged		AAM-1 Unaged		OD1 Unaged		OD3 Unaged		Avg
	Tcr, ºC	SD ºC	Tcr, ºC	SD, ºC	Tcr, ºC	SD, ºC	Tcr, ºC	SD, ºC	Tcr, ºC	SD, ºC	Tcr, ºC	SD, ºC	SD
1	-35.3	1.1	-40.6	0.8	-24.7	0.7	-31.9	0.6	-34.9	0.3	-39.0	0.2	0.62
3	-33.9	0.5	-37.0	0.9	-22.2	0.7	-32.6	1.0	-33.8	0.5	-38.6	1.1	0.78
10	-31.7	0.5	-36.5	1.7	-20.8	1.5	-31.2	0.4	-33.0	0.1	-37.2	1.0	0.86
20	-32.2	0.7	-36.4	0.6	-19.6	0.7	-31.6	1.0	-32.9	1.0	-37.8	0.6	0.77
40	-32.0	1.6	-35.1	1.3	-18.7	0.9	-30.0	1.9	-31.7	0.6	-36.4	1.5	1.23

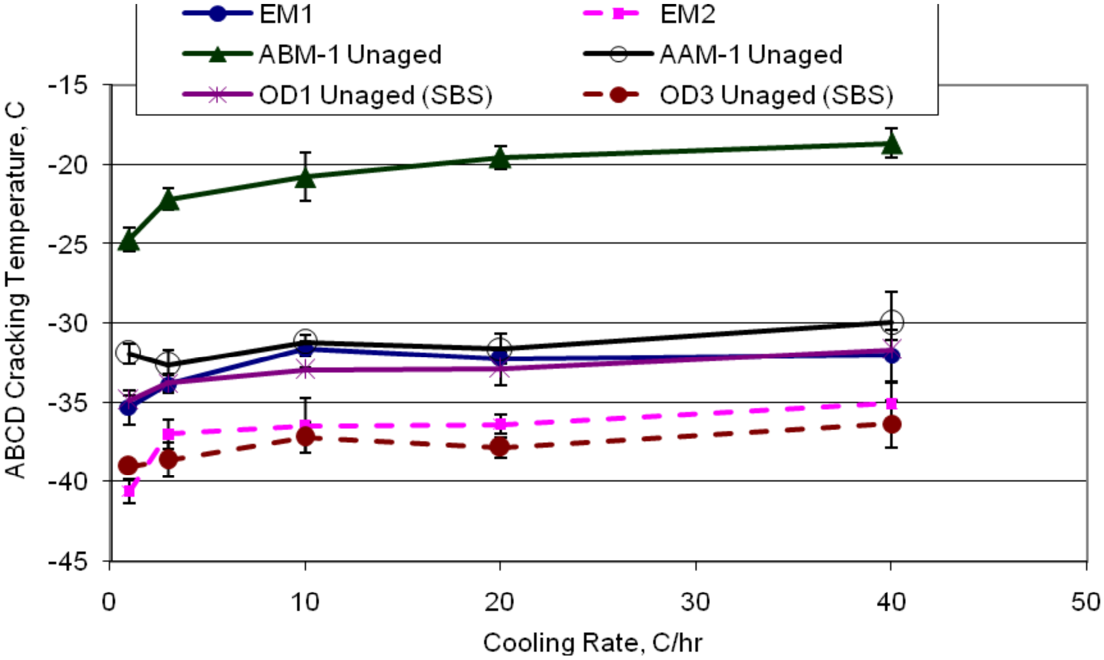

Figure 1. The effects of cooling rate on ABCD cracking temperature and repeatability (vertical bars indicate one standard deviation from their average cracking temperatures)

The two polymer modified binders show trends similar to those seen in the unmodified binders. There is a clear trend between the ABCD cracking temperature and the cooling rate. As the rate of cooling increases, the cracking temperature of the asphalt specimens increases (specimen cracks at warmer temperatures). This agrees with the viscoelastic nature of asphalt binders. At a higher cooling rate, the rate of thermal stress accumulation is faster than the rate of stress relaxation, leading to rapid stress development and early/warm fractures. Except AAM-1 unaged, the rate increase from 1ºC/hr to 3ºC/hr resulted in a significant increase in cracking temperature (4.5ºC on average). However, subsequent rate increases greater than 3ºC/hr did not affect cracking temperature as significantly as at rates less than 3ºC/hr. For all cooling rates, the rank of the thermal cracking resistance of the four asphalt binders remained the same. The standard deviations of four ABCD measurements were less then 1.00ºC for all cooling rates except the highest cooling rate, 40ºC/hr. The results of the cooling rate tests suggest that the use of a 20ºC/hour cooling rate provides the same repeatability of ABCD cracking temperatures as a 10ºC/hour cooling rate for both unmodified and polymer modified binders.

The relationship between ABCD cracking temperature and cooling rate can be summarized by a multiple linear regression as given below.

Tcr = -38.88 + 0.74*(Cooling Rate) + (Binder Constant) ($r^2 = 0.94$)

Where, Tcr = ABCD Cracking Temperature, ºC

Cooling Rate = in ºC/hour
Binder Constants
EM1 = 4.73
EM2 = 0.70
ABM1 Una = 16.69
AAM1 Una = 6.26
OD1 Una = 4.53
OD1 Una = 0.00

The measured ABCD cracking temperatures and the predicted values using the above predictive equations are plotted in Figure 2. As cooling rate increases by 1ºC/hour (faster cooling), the ABCD cracking temperature increases (warms) by 0.074 ºC. Similar results will be obtained for log-transformed cooling rate data.

More asphalt binders were tested at the 20ºC/hour cooling rate and compared with the results of 10ºC/hour cooling rate test as summarized in Table 6. Differences are less than 0.5ºC except AAC-1 and AAM-1 asphalt binders (both binders are known to be waxy).

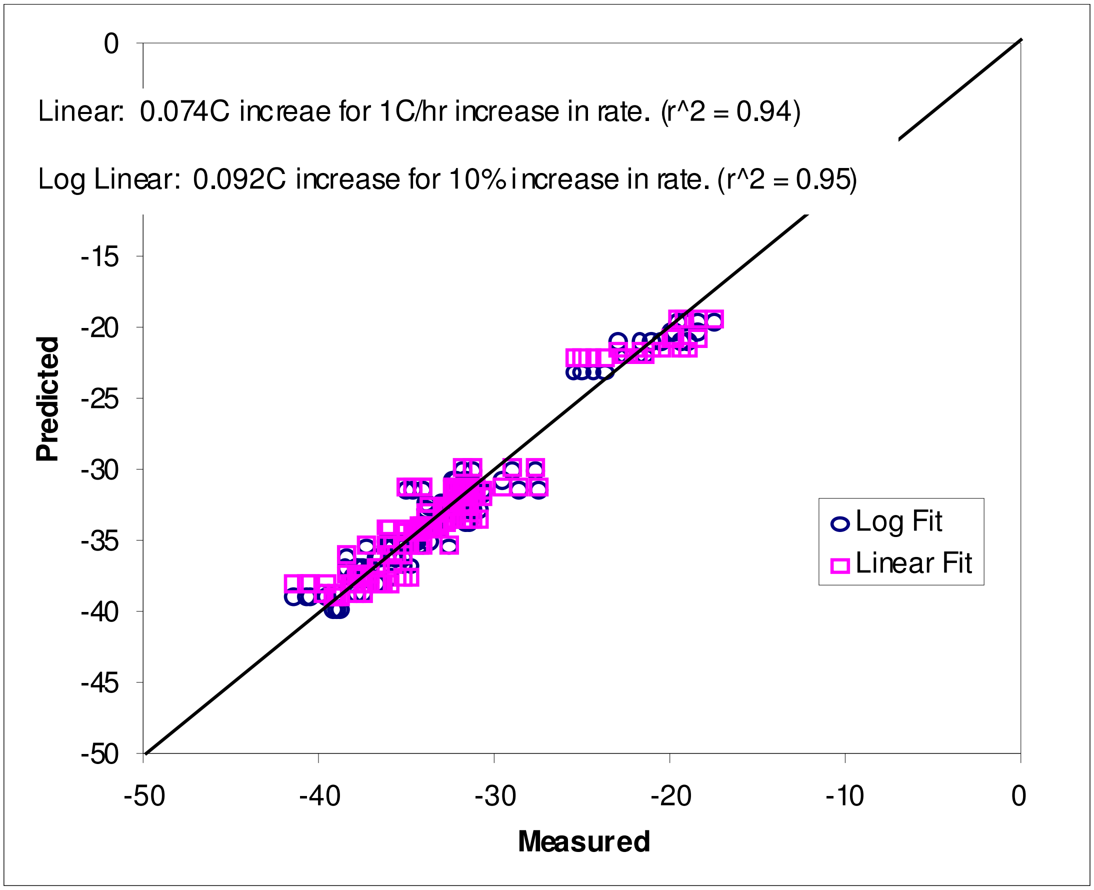

Figure 2. Predicted and measured ABCD cracking temperatures at various cooling rates.

Table 6. Comparison of 10ºC/hour and 20ºC/hour test results

ID	Aging	ABCD Cracking Temperature, C				
		20C/hr		10C/hr		Diff (20-10C/hr)
		Avg	SD	Avg	SD	
AAA-1	Unaged	-38.3	1.37	-38.0	0.99	-0.2
AAB-1	Unaged	-34.7	0.73	-34.7	0.79	0.0
AAC-1	Unaged	-34.4	1.05	-35.9	1.10	1.5
AAF-1	Unaged	-29.0	0.92	-29.0	1.00	0.0
AAM-1	Unaged	-33.4	0.85	-31.1	0.15	-2.3
ABM-1	Unaged	-19.6	0.7	-20.8	1.50	1.2
OD1 (SBS)	Unaged	-33.2	1.06	-33.0	0.13	-0.2
OD2	Unaged	-30.0	0.46	-29.8	0.61	-0.2
OD3 (SBS)	Unaged	-37.7	0.71	-37.2	0.96	-0.5
OD4 (SBS)	Unaged	-38.8	0.72	-39.7	0.38	-0.9
Average			**0.86**		**0.76**	**-0.16**

1B. Physical Hardening

During SHRP, it was found that the phenomenon known as physical hardening (or physical aging) in polymers also existed in asphalt binders. When an asphalt binder is kept at low temperatures for an extended period of time, its modulus increases with time. Unaged and RTFO/PAV aged SHRP core asphalt binders were used to determine the effects of physical hardening on the ABCD cracking temperature. The environmental chamber was programmed to hold the chamber air temperature at -15ºC for 24 hours before cooling it at a rate of 10ºC/hour. During this 24 hour isothermal conditioning, the sample temperatures were between -14.1ºC and -14.8ºC depending on the location of the specimen in the chamber and remained constant with a temperature fluctuation less then 0.15ºC. The summary of the physical hardening effect on ABCD tests is presented in Table 7.

A statistical analysis was performed to determine the effects of three independent variables (asphalt source, aging, and physical hardening) on the ABCD cracking temperature. A three factor analysis of variance (ANOVA) is given in Table 8. The interaction among binder type, aging status and isothermal conditioning (Aspalt*Aging*PH) is very significant (p-value < 0.01). This means that the effects of physical hardening on ABCD cracking temperature is statistically significant and differs for aging status and binder type. As shown in Figure 3, for unaged binders, the 24 hours of isothermal conditioning at -15ºC caused the ABCD cracking temperatures to rise significantly. However, the effects of physical hardening are quite different for aged binders. For RTFO/PAV aged binders, the 24 hour conditioning at -15ºC significantly lowered cracking temperature. At this time, there is no good explanation for these different trends for unaged and aged binders. In general, the repeatability of the ABCD cracking temperature became poorer when subjected to the long isothermal conditioning. On average for all binders, the standard deviations for the ABCD test with and without the 24 hour conditioning at -15ºC were 1.1ºC and 0.9ºC, respectively.

Table 7. Physical hardening effects on ABCD cracking temperature of PAV aged and unaged SHRP core asphalt binders.

7a) 10C/hr ABCD test after 24 hour conditioning at -15C

Binder	Aging	ABCD Cracking Temperature, C					**SD**
		Rep1	Rep2	Rep3	Rep4	**Avg**	
AAA-1	PAV	-33.6	-36.0	-38.2	-37.4	**-36.3**	**2.02**
AAB-1	PAV	NM	-31.5	-31.5	-31.3	**-31.4**	**0.12**
AAC-1	PAV	-34.1	-32.1	NM	-31.1	**-33.1**	**1.41**
AAD-1	PAV	-34.8	-33.7	-35.1	-31.9	**-34.5**	**0.74**
AAF-1	PAV	-25.1	-24.5	-24.8	-24.8	**-24.8**	**0.24**
AAK-1	PAV	-29.7	-28.7	-29.4	-30.6	**-36.1**	**0.54**
AAM-1	PAV	-31.2	-34.9	-31.7	NM	**-32.6**	**2.01**
ABM-1	PAV	-19.7	-18.7	-20.9	-20.3	**-19.9**	**0.94**
AAA-1	Unage	-37.4	-37.8	-41.3	-38.6	**-38.8**	**1.76**
AAB-1	Unage	-33.8	-32.0	-35.8	-32.4	**-33.9**	**1.90**
AAC-1	Unage	-32.6	-33.0	NM	-33.8	**-32.8**	**0.28**
AAD-1	Unage	-38.7	-37.4	-39.9	-37.3	**-38.3**	**1.23**
AAF-1	Unage	-25.8	-26.6	-26.4	-26.9	**-26.4**	**0.46**
AAK-1	Unage	-32.4	-33.0	-33.5	-32.7	**-33.0**	**0.55**
AAM-1	Unage	-29.5	-29.9	NM	-26.1	**-28.5**	**2.09**
ABM-1	Unage	-21.6	-22.1	-21.9	-21.7	**-21.9**	**0.25**

7b) 10C/hr ABCD test without conditioning at -15C

Binder	Aging	ABCD Cracking Temperature, C					**SD**
		Rep1	Rep2	Rep3	Rep4	**Avg**	
AAA-1	PAV	-36.4	-37.3	-36.1	-36.0	**-36.5**	**0.59**
AAB-1	PAV	-31.3	-32.4	-31.7	-32.2	**-31.9**	**0.50**
AAC-1	PAV	-32.2	-31.7	-32.3	-32.8	**-32.3**	**0.45**
AAD-1	PAV	-32.3	-32.7	-31.6	-31.8	**-32.1**	**0.50**
AAF-1	PAV	-23.4	-24.0	-25.2	-25.6	**-24.6**	**1.02**
AAK-1	PAV	-27.7	-28.7	NM	-29.6	**-28.7**	**0.95**
AAM-1	PAV	-27.6	-29.2	NM	-30.4	**-29.1**	**1.40**
ABM-1	PAV	-16.0	-18.1	NM	-17.5	**-17.2**	**1.08**
ABM-1	PAV	-16.9	NM	-17.2	-19.0	**-17.7**	**1.14**
AAA-1	Unage	-38.4	-37.4	-37.0	-39.3	**-38.0**	**1.03**
AAA-1	Unage	-37.2	-39.3	-38.6	-37.0	**-38.0**	**1.11**
AAB-1	Unage	-34.8	-34.4	-35.4	-34.9	**-34.9**	**0.41**
AAB-1	Unage	-34.4	-34.5	-33.3	-36.0	**-34.6**	**1.11**
AAC-1	Unage	-34.4	-36.8	-36.6	-35.6	**-35.9**	**1.10**
AAD-1	Unage	NM	-38.9	-40.2	-38.7	**-39.3**	**0.81**
AAD-1	Unage	-39.8	-36.9	-37.4	-39.3	**-38.4**	**1.42**
AAF-1	Unage	-29.9	-29.4	-30.4	-29.2	**-29.7**	**0.54**
AAF-1	Unage	-27.4	-29.0	-29.1	-27.8	**-28.3**	**0.85**
AAK-1	Unage	-34.0	-33.3	-33.3	-36.4	**-34.3**	**1.47**
AAK-1	Unage	-36.1	-32.2	NM	-34.9	**-34.4**	**2.00**
AAM-1	Unage	-31.3	-31.0	NM	-31.1	**-31.1**	**0.15**
ABM-1	Unage	-21.5	-22.5	-23.6	-20.6	**-22.1**	**1.29**
ABM-1	Unage	-19.0	-21.7	-21.0	-23.0	**-21.2**	**1.67**

NM : Not Measured

Table 8. Analysis of Variance (ANOVA) of ABCD cracking temperature; effects of asphalt source, aging and physical hardening.

Dependent Variable: Tcr

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	5023.6(a)	31	162.1	123.5	0.000
Intercept	124595.0	1	124595.0	94964.6	0.000
Asphalt	4066.6	7	580.9	442.8	0.000
Aging	239.6	1	239.6	182.6	0.000
PH	0.3	1	0.3	0.2	0.636
Asphalt * Aging	94.1	7	13.4	10.2	0.000
Asphalt * PH	26.9	7	3.8	2.9	0.007
Aging * PH	43.7	1	43.7	33.3	0.000
Asphalt * Aging * PH	25.9	7	3.7	2.8	0.010
Error	146.9	112	1.3		
Total	143387.2	144			
Corrected Total	5170.6	143			

[a] R Squared = 0.972 (Adjusted R Squared = 0.964)

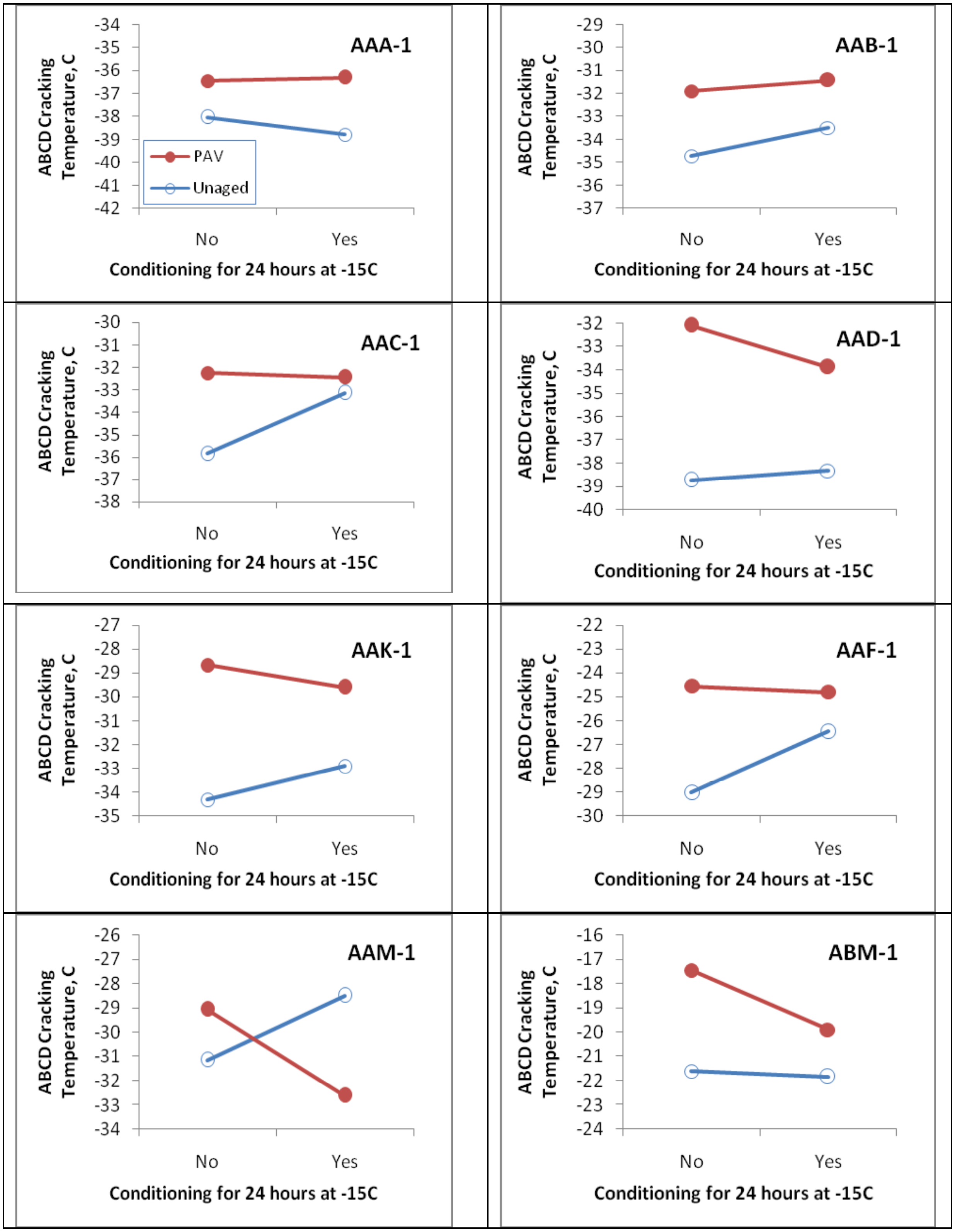

Figure 3. Physical hardening effects on SHRP core asphalt binders.

1C. Refinement of Test Procedures

To help increase the ease and consistency of ABCD sample preparation, the use of turntables was incorporated into the procedure. Sixteen additional aluminum turntables were made for the ruggedness test program. For sample pouring, silicone molds were placed on 4 in. x 4 in. x 1/8 in. aluminum turntables. A tin cup holding the heated asphalt was placed on a pouring platform. As a sample was poured, the mold on the turntable was slowly turned. These turntables helped greatly in preventing overfilling and spillage due to misalignment of the pouring stream and the ¼ in. annular gap between the ABCD ring and the mold. The aluminum turntable also served as a rigid support for the flexible silicone mold. After pouring and trimming, the sample (consisting of ABCD ring, binder, mold, and turntable) was moved to the environmental chamber. The flat smooth surface of the turntable on which the sample rested reduced the risk of deforming the sample shape by accidental bending of the mold. Overall, it was felt that use of turntables enabled cleaner pouring of samples, thus easier and more consistent trimming. The cleaner trimming further enabled easier cleaning of molds and ABCD rings following the tests. The use of a turntable was added to the ruggedness test program as a variable to be tested.

In comparison with the results of EZ Asphalt Technology laboratory tests, ABCD test results of two other participating laboratories showed larger variability. From the follow-up investigation, ABCD sample preparation procedures were modified. After pouring asphalt binder in the molds, they were allowed to cool to room temperature for one hour (instead of cooling at 0℃ for 20 minutes). Then, the rings were rotated between 5 and 30 degrees and back prior to trimming. These two changes made a significant improvement in the repeatability of the ABCD test. The details are further discussed in the sections for “Ruggedness Test” and “Pilot Interlaboratory Study”. These modifications to the test procedures are reflected in the procedures presented in Appendices B and C.

Task 2. Field Validation

In addition to the originally proposed asphalt binders from National Pooled Fund Study 776 and four Ohio DOT paving projects, eight SHRP binders were included in this Task. These SHRP binders were extensively studied during and after SHRP and their low temperature characteristics are well known. The results of ABCD testing with 10ºC/hour cooling rate results are given in Tables 9, 10, and 11. The strength of asphalt binders as measured by Direct Tension Tester (DTT) and ABCD are also compared as shown in Table 12 and Figure 4. As shown in Figure 4, there is a moderate relationship between ABCD strain jump and DTT failure stress for unaged SHRP binders but no statistically significant relationship for PAV aged binders. There is a significant difference in strength measurement between DTT and ABCD. While test temperature is fixed in DTT determination of strength, the temperature cannot be fixed in ABCD test due to ABCD's direct means for determining the cracking temperature. For comparison purposes, DTT strength measured at the lowest temperatures are presented.

Field performance of the Ohio DOT binders are not available. Binder and mixture samples of test roads constructed for Pooled Fund Study 776 Phase II will be tested as they becomes available.

Table 9. ABCD test results for asphalt binders from National Pooled Fund Study 776 Phase I

ID	Aging	ABCD Cracking Temperature, ºC				**Average**	**StDev**
		1	2	3	4	ºC	ºC
MN 1	PAV	-53.4	-53.9	ND	-54.7	**-54.0**	**0.66**
MN 2	PAV	-39.1	-39.6	ND	-40.7	**-39.8**	**0.82**
MN 3	PAV	-42.5	-41.8	ND	-42.5	**-42.3**	**0.40**
MN 4	PAV	-37.3	-35.2	ND	-35.4	**-36.0**	**1.16**
MN 5	PAV	-35.6	-34.4	ND	-34.6	**-34.9**	**0.64**
MN 6	PAV	-40.4	-39.0	ND	-40.7	**-40.0**	**0.91**
MN 7	PAV	-42.1	-43.9	ND	-43.7	**-43.2**	**0.99**
MN 8	PAV	-36.3	-36.7	ND	-35.9	**-36.3**	**0.40**
MN 9	PAV	-40.3	-43.0	-41.3	-41.6	**-41.6**	**1.12**
MN 10	PAV	ND	ND	ND	ND	ND	ND

ND: not determined

Table 10. ABCD test results for SHRP asphalt binders.

ID	Aging	ABCD Cracking Temperature, ºC				**Average**	**StDev**
		1	2	3	4	ºC	ºC
AAA-1	PAV	-36.4	-37.3	-36.1	-36.0	**-36.5**	**0.59**
AAB-1	PAV	-31.3	-32.4	-31.7	-32.2	**-31.9**	**0.50**
AAC-1	PAV	-32.2	-31.7	-32.3	-32.8	**-32.3**	**0.45**
AAD-1	PAV	-32.3	-32.7	-31.6	-31.8	**-32.1**	**0.50**
AAF-1	PAV	-23.4	-24.0	-25.2	-25.6	**-24.6**	**1.02**
ABM-1	PAV	-16.9	-17.2	ND	-19.0	**-17.7**	**1.14**
AAK-1	PAV	-27.7	-28.7	ND	-29.6	**-28.7**	**0.95**
AAM-1	PAV	-27.6	-29.2	ND	-30.4	**-29.1**	**1.40**
AAA-1	RTFO	-38.4	-34.7	ND	-37.7	**-36.9**	**1.97**
AAB-1	RTFO	-32.6	-32.2	ND	-33.5	**-32.8**	**0.67**
AAC-1	RTFO	-32.2	-31.8	ND	-31.6	**-31.9**	**0.31**
AAD-1	RTFO	-35.2	-36.0	ND	-34.4	**-35.2**	**0.80**
AAF-1	RTFO	-30.0	-31.3	ND	-31.7	**-31.0**	**0.89**
ABM-1	RTFO	-18.6	-17.3	ND	-18.4	**-18.1**	**0.70**
AAA-1	Unaged1	-37.2	-39.3	-38.6	-37.0		
	Unaged2	-38.4	-37.4	-37.0	-39.3	**-38.0**	**0.99**
AAB-1	Unaged1	-34.4	-34.5	-33.3	-36.0		
	Unaged2	-34.8	-34.4	-35.4	-34.9	**-34.7**	**0.79**
AAC-1	Unaged	-34.4	-36.8	-36.6	-35.6	**-35.9**	**1.10**
AAD-1	Unaged1		-38.9	-40.2	-38.7		
	Unaged2	-39.8	-36.9	-37.4	-39.3	**-38.7**	**1.21**
AAF-1	Unaged1	-27.4	-29.0	-29.1	-27.8		
	Unaged2	-29.9	-29.4	-30.4	-29.2	**-29.0**	**1.00**
ABM-1	Unaged1	-19.0	-21.7	-21.0	-23.0		
	Unaged2	-21.5	-22.5	-23.6	-20.6	**-21.6**	**1.46**
AAK-1	Unaged1	-34.0	-33.3	-33.3	-36.4		
	Unaged2	-36.1	-32.2	ND	-34.9	**-34.3**	**1.56**
AAM-1	Unaged	-31.3	-31.0	ND	-31.1	**-31.1**	**0.15**

ND: not determined

Table 11. ABCD test results for Asphalt binders from 4 Ohio 2007 paving projects.

ID	Aging	ABCD Cracking Temperature, ºC				**Average**	**StDev**
		1	2	3	4	ºC	ºC
OD1	Unaged	-33.1	-32.8	-33.0	-32.9	**-33.0**	**0.13**
OD2	Unaged	-29.0	-30.1	-30.4	-29.6	**-29.8**	**0.61**
OD3	Unaged	-35.9	-38.2	-37.1	-37.5	**-37.2**	**0.96**
OD4	Unaged	-40.0	-40.0	-39.2	-39.7	**-39.7**	**0.38**

Table 12. Comparison of Binder Strength measured by DTT and ABCD.

	DTT		ABCD	
	Temp	Fail Stress	Strain Jump	St. Dev.
	C	MPa	µå	µå
Unaged Binders				
AAA-1	-20	1.02	23.2	4.87
AAB-1	-20	1.57	24.1	3.19
AAC-1	-20	1.95	39.2	8.46
AAD-1	-20	0.97	28.3	8.29
AAF-1	-17	1.99	24.9	4.92
AAG-1 /ABM-1	-10	1.14	21.4	7.29
AAK-I	-20	1.48	25.8	8.11
AAM-1	-20	3.23	37.2	8.80
PAV binders				
AAA-1	-15	1.18	22.3	5.09
AAB-1	-15	1.44	25.0	1.06
AAC-1	-15	2.28	31.6	7.85
AAD-1	-15	1.71	23.6	4.44
AAF-1	-5	1.72	24.2	4.82
AAG-1 /ABM-1	-5	2.55	27.8	5.86
AAK-I	-10	0.99	27.0	4.81
AAM-1	-15	3.84	27.2	5.55

DTT data from SHRP A 369 report, Tables 4-10 & 4-12

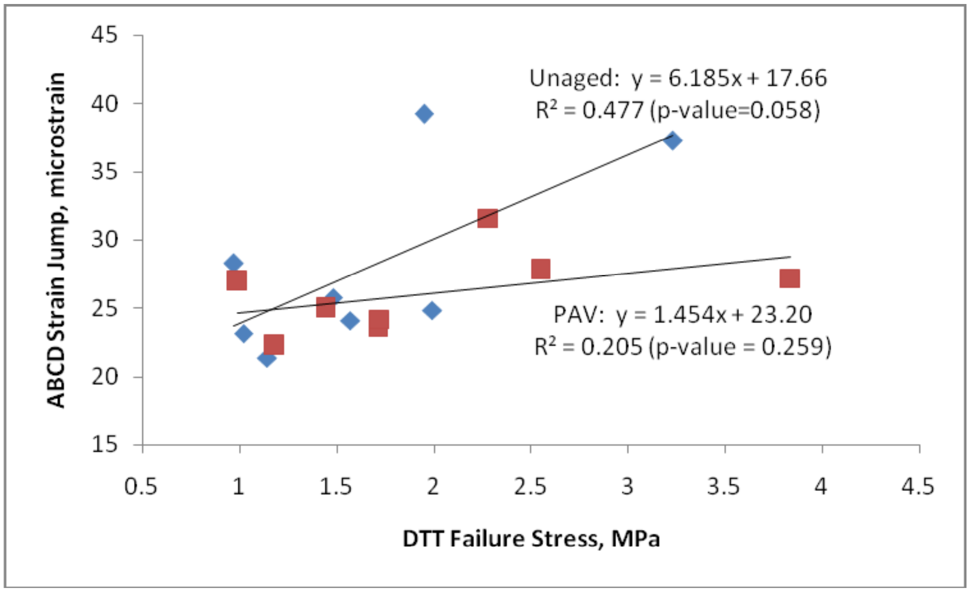

Figure 4. Comparison of strength measured by DTT and ABCD

<u>**Task 3. Refinement of Equipment and Analysis Software**</u>

3A. Free Piston Sterling Cooler (FPSC)

In collaboration with Global Cooling, Inc., the manufacturer of the Free Piston Sterling Cooler (FPSC), a prototype environmental chamber using the FPSC was developed specifically for ABCD testing. The prototype FPSC chamber is light-weight, quiet, and free of vibration. The FPSC chamber was tested for use with the ABCD. In all trials, the FPSC chamber could not maintain the desired cooling rate (20ºC/hr) as shown in Figure 5. At temperatures warmer than -30ºC, the cooling rate was larger than 20ºC/hr and at temperature colder than -30ºC, the rate was lower than 20ºC/hr. Some of the problems may be due to insufficient air circulation and low cooling capacity. Even though new fans and modifications to the FPSC may solve the problem, further use of the FPSC-based chamber was put on hold. The Cincinnati Sub-Zero Products, Inc., cooling chamber that has been used for the majority of ABCD development has proven to be durable with consistent cooling rates.

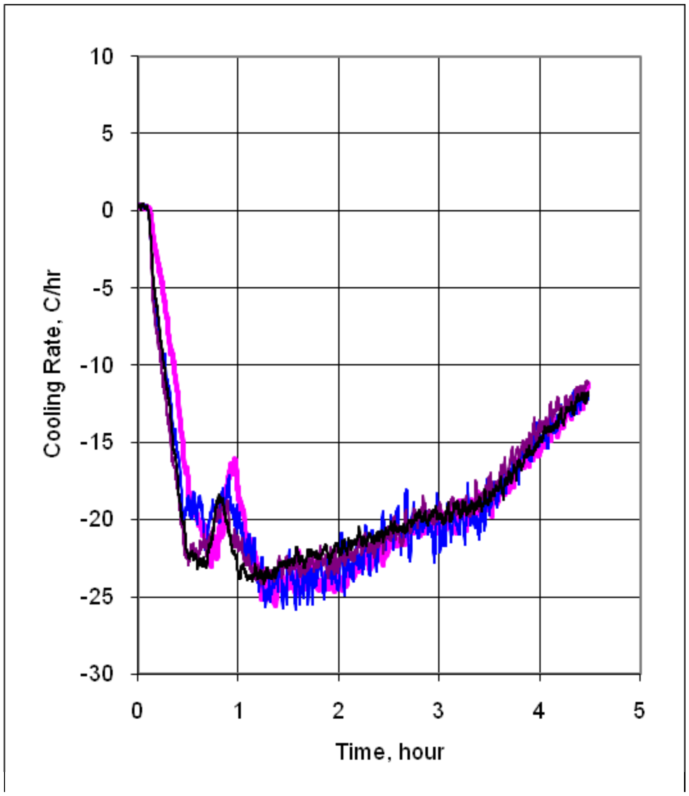

Figure 5. Temperature profile of the fist FPSC chamber with 4 ABCD samples (target cooling rate after 1 hour = 20ºC/hr).

3B. ABCD Ring

During the extensive testing of ABCD, it has been noticed that if the cooling chamber is opened while still at low temperature, condensation collects on the ring materials. The ABCD software instructs the cooling chamber to warm-up to room temperature upon completion of the cooling cycle - to avoid condensation. However, an operator could interrupt the test and open the chamber door while the chamber is still cold. The continuous use of the ABCD ring under such conditions leads to excessive moisture accumulation inside the ring, causing strain gage failure. To eliminate the moisture problem, sensors inside new rings were coated with water proofing materials. The water proofing consisted of two coats of flexible water proofing material. The water proofing material was commercially available solvent-thinned silicone rubber which cured to a tough rubbery non-corrosive film. The film thickness of each coat was approximately 0.015 to 0.02 in. thick (per manufacturer literature). After applying water proofing, the rings were tested under water for 24 hours. The results (Figure 6) show that the water proofing was effective. The problem caused by moisture is believed to be minimal for the water proofed ABCD rings.

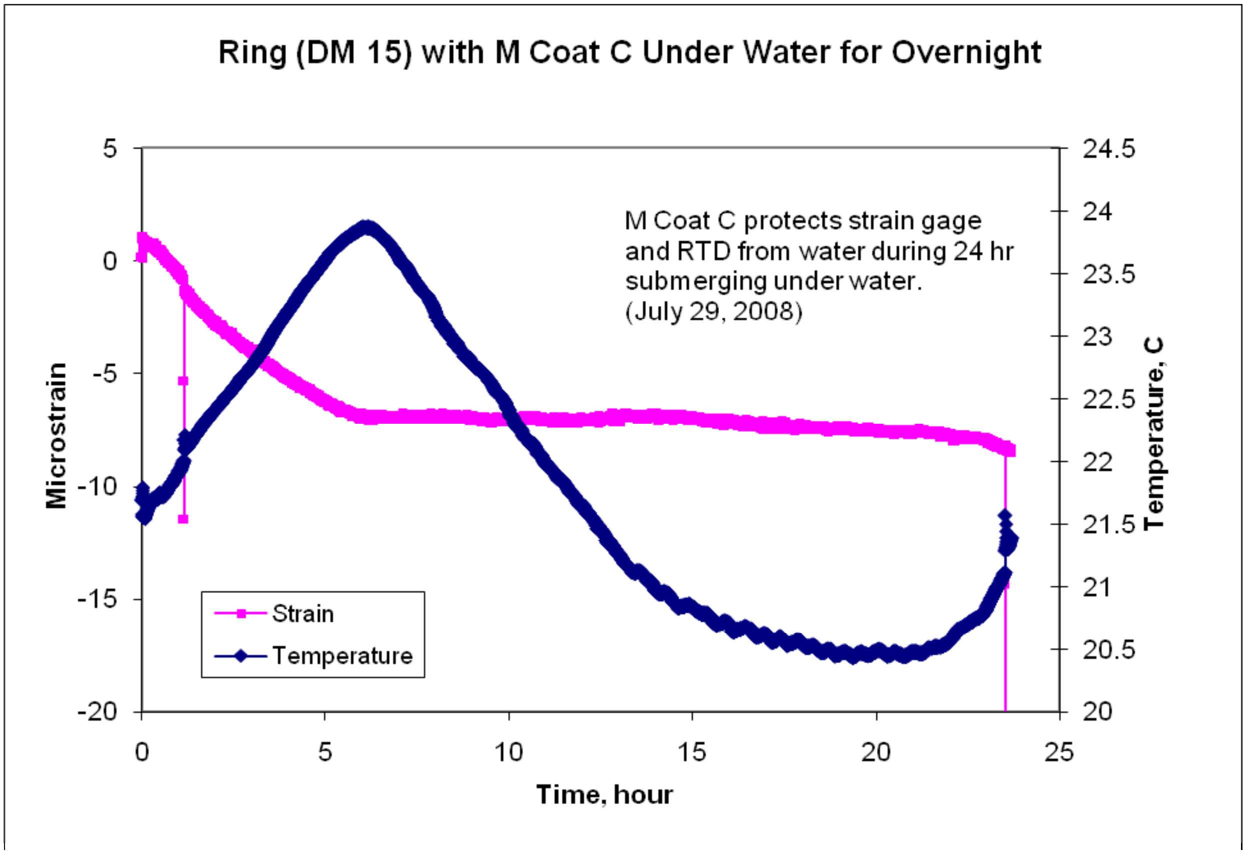

Figure 6. ABCD ring measurements under water after water-proofing (strain spikes at beginning and end were intentionally caused by operator to check the sensors' response).

3C. ABCD Data Analysis Software

The ABCD test data (time, temperature, and strain measurement from each ABCD ring) are recorded by National Instrument's LabVIEW program which displays real-time graphs of strain and temperature versus elapsed time. The program has been upgraded so that it can be used for both Microsoft Windows XP and Vista operating systems. Further, the software now provides direct control of the temperature within the environmental chamber allowing the user to control the rate that the temperature drops within the chamber. The program is now linked to the data analysis program. At the end of the each run, the just-completed data files open automatically. Then, the operator simply clicks on the data analysis menu to run the data analysis program to obtain ABCD test results (cracking temperatures, strength, cooling rate, etc.). The details of the test sotware and data analysis procedure can be found in Appendix D (ABCD User's Manual).

Task 4. Ruggedness Test

The purpose of the ruggedness test is to identify sources of variation in ABCD testing. ABCD units and asphalt binder samples were delivered to North Central Superpave Center (NC) and University of Wisconsin, Madison (WI) asphalt laboratories. Sang-Soo Kim of EZ Asphalt provided one day on-site training at each laboratory to the equipment operators (August 25-27, 2008). The ruggedness test was designed following ASTM C 1067 – 00 “Standard Practice for Conducting A Ruggedness or Screening Program for Test Methods for Construction Materials”. Of seven factors considered, the effect of lubrication was dropped from the test since conducting the ABCD test without lubrication might seriously damage ABCD rings during cleaning.

4A. Seven factors being studied in Ruggedness Test

1. Cooling Rate (18°C/hr versus 22°C/hr)
   Temperature profiles to be used is

18°C/hr	22°C/hr
20¡ÆC to 0¡ÆC in 0.5 hour (30 minutes) 0¡ÆC to -63¡ÆC in 3.5 hours (3 hour 30 minutes) -63 to 25°C in 0.5 hour (30 minutes) Hold at 25°C for 1.0 hour	20¡ÆC to 0¡ÆC in 0.5 hour (30 minutes) 0¡ÆC to -66¡ÆC in 3.0 hours -66 to 25°C in 0.5 hour (30 minutes) Hold at 25°C for 1.0 hour

2. Size of Protrusion (5.85mm diameter vs. 6.35mm diameter [0.23” versus 0.25”])
   The two larger protrusion molds also have a hole at the opposite side.

3. Sample Trimming (0.8mm over trimming versus even trimming)
   For over trimming, 0.8 mm depression (about 5 cm long) is created at the surface of two silicone molds. Carefully trim the asphalt binder so that the trimmed surface is flush with the mold surface.

4. ~~Lubrication (No Lubrication versus Lubrication)~~
   ~~Two molds and 2 ABCD rings are lubricated with glycerin-talc mixture.~~
   ~~The other 2 molds and rings are kept clean and dry without lubrication.~~

5. No Turntable versus Turntable
   For ‘no turntable test’, carefully conduct pouring, trimming, testing and other handling without the use of turntable. For turntable test, place the molds on the turntable and then perform pouring, trimming, testing and other handling.

6. No cold joint versus cold joint
   To create cold joints in ABCD sample, fill the mold ½ full with the heated asphalt binder. Place the half filled mold in 0°C chamber for 5 minutes and place the binder container back in the 170° oven for 5 minutes. After 5 minutes, completely fill the mold with the heated asphalt binder.

7. Conditioning time before starting test (0 minute vs. 30 minutes)
   All 4 samples are placed in 0°C chamber at the same time. For 30 minute conditioning time, remove two samples after 20 minutes from the 0°C chamber. Trim the sample

and then place them in the room temperature for 30 minutes. The other two samples are removed after 50 minutes at the 0℃ chamber. Trim them and then start the test immediately.

Each lab was instructed to follow test procedure given below.

The laboratories used the following mold identification numbers:
Mold #1: Smaller diameter (0.23”) protrusion and no depression on the surface.
Mold #2: Smaller diameter (0.23”) protrusion and 0.8mm depression on the surface.
Mold #3: Larger diameter (0.25”) protrusion and no depression on the surface.
Mold #4: Larger diameter (0.25”) protrusion and 0.8mm depression on the surface.

For Each Binder

Run #1: 18℃/hr Test (4 specimens)

	Mold #1	Mold #2	Mold #3	Mold #4
Cooling Rate	18℃/hr	18℃/hr	18℃/hr	18℃/hr
~~Lubrication~~	~~Lubricate~~	~~Lubricate~~	~~None~~	~~None~~
Turn Table	None	Turn Table	None	Turn Table
Cold Joint	None	Cold Joint	Cold Joint	None
Conditioning Time	30 minutes	0 minute	0 minute	30 minutes
	Data #1	Data #2	Data #3	Data #4

Run #2: 22℃/hr Test (4 specimens)

	Mold #1	Mold #2	Mold #3	Mold #4
Cooling Rate	22℃/hr	22℃/hr	22℃/hr	22℃/hr
~~Lubrication~~	~~None~~	~~None~~	~~Lubricate~~	~~Lubricate~~
Turn Table	Turn Table	None	Turn Table	None
Cold Joint	None	Cold Joint	Cold Joint	None
Conditioning Time	0 minutes	30 minute	30 minute	0 minutes
	Data #5	Data #6	Data #7	Data #8

Repeat Run #1 and Run #2

Repeat Run #1: 18℃/hr Test (4 specimens)

	Mold #1	Mold #2	Mold #3	Mold #4
Cooling Rate	18℃/hr	18℃/hr	18℃/hr	18℃/hr
~~Lubrication~~	~~Lubricate~~	~~Lubricate~~	~~None~~	~~None~~
Turn Table	None	Turn Table	None	Turn Table
Cold Joint	None	Cold Joint	Cold Joint	None
Conditioning Time	30 minutes	0 minute	0 minute	30 minutes
	Data #9	Data #10	Data #11	Data #12

Repeat Run #2: 22℃/hr Test (4 specimens)

	Mold #1	Mold #2	Mold #3	Mold #4
Cooling Rate	22℃/hr	22℃/hr	22℃/hr	22℃/hr
~~Lubrication~~	~~None~~	~~None~~	~~Lubricate~~	~~Lubricate~~
Turn Table	Turn Table	None	Turn Table	None
Cold Joint	None	Cold Joint	Cold Joint	None

Conditioning Time	0 minutes	30 minute	30 minute	0 minutes
	Data #13	Data #14	Data #15	Data #16

‘No Lubrication’ was dropped due to the possibility of damaging ABCD rings.

The four binders used in the study are as follows

EZ 1	EZ 2	EZ 3	EZ 4
PG 64-16 (AAM-1)	PG 70-22M (SBS)	PG 58-28 (AAA-1)	PG 64-34M (SBS)

All binders were RTFO aged followed by PAV aging and degassing prior to sending them to the participating laboratories. The specimen cooling rate is determined by the slope of the best fit line of ten data points (about 0.56°C change during 100 seconds) prior to cracking. The average and the standard deviation of the specimen cooling rate of test specimens for each lab are as follows:

Laboratory	WI		NC		EZ	
Cooling Rate	Low	High	Low	High	Low	High
Average, °C/hr	-18.6	-22.8	-18.7	-22.9	-18.8	-23.2
st. dev., °C/hr	0.25	0.55	0.32	0.38	0.30	0.93

When the slope of a longer time period is used, the specimen cooling rate approaches the intended rates (18 and 22°C/hr).

4B. Ruggedness Test Results

4B.1. ABCD Cracking Temperature

On November 15, 2008, the last set of ruggedness test results were received. Following ASTM C 1067, ABCD cracking temperature data (Table 13) were analyzed and summarized in Table 14. Following the ASTM ruggedness analysis procedure, any factors with F Statistics greater than 5.59 are considered to have significant effects on ABCD cracking temperature with 5% significance level. Standard deviation is the Root-Mean-Square-Error (RMSE). When reviewed for each combination of four asphalt binder types and three laboratories, there are 12 cases as shown in Table 14. The size of protrusion and the over-trimming were the factors affecting test results most significantly (four significant cases each). Formation of a cold joint during sample preparation had two significant cases. Cooling rate and conditioning time had one significant case each.

The required ASTM ruggedness analyses presented in the previous paragraph addressed the significant variables at a given laboratory and for a given asphalt binder. The required analyses do not directly compare the laboratories statistically. Therefore, in addition to the required analyses, EZ Asphalt investigated the overall statistical differences using Analysis of Variance (ANOVA) with the results shown in Table 15. As expected, ABCD cracking temperature clearly differentiates between asphalt types (F value = 436, p-value < 0.001). However, there are significant variations in cracking temperature between laboratories. Among the ruggedness factors, only ‘Over Trim’ is statistically significant in affecting ABCD cracking temperature (significance level less than 1%).

Table 13. Results of Ruggedness Test.

Lab	Binder ID	Data: ABCD Cracking Temperature, C															
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
WI	EZ 1	-31.2	-26.8	-30.1	-29.4	-34.8	-32.0	-32.9	-30.4	-33.3	-33.7	-33.8	-30.8	-30.4	-29.5	-30.8	-31.4
	EZ 2	-41.0	-37.7	-39.3	-42.2	-38.6	-40.1	-42.9	-37.5	-41.5	-36.9	-38.4	-39.2	-39.0	-40.3	-42.1	-38.3
	EZ 3	-35.6	-40.0	-37.9	-35.7	-37.4	-39.5	-38.4	-37.9	-41.9	-37.4	-40.1	-37.3	-38.6	-39.9	-40.8	-35.5
	EZ 4	-48.3	-47.1	-47.3	-44.8	-50.8	-48.5	-48.8	-46.0	-45.3	-42.4	-47.0	-44.9	-47.4	-45.4	-46.5	-45.4
NC	EZ 1	-30.2	-30.6	-30.3	-28.3	-31.2	-32.9	-27.4	-28.5	-32.4	-32.6	-28.7	-30.3	-33.2	-31.4	-32.9	-31.8
	EZ 2	-32.1	-32.2	-35.8	-32.6	-36.1	-33.6	-33.5	-35.9	-34.9	-33.4	-34.9	-38.9	-33.2	-32.7	-35.2	-37.6
	EZ 3	-39.1	-36.3	-36.5	-36.1	-35.6	-37.1	-35.8	-36.7	-38.1	-37.6	-31.8	-34.7	-37.7	-36.6	-35.1	-36.8
	EZ 4	-46.3	-40.8	-45.3	-41.0	-44.9	-46.6	-39.6	-41.9	-41.3	-40.3	-41.9	-41.2	-43.9	-39.4	-43.1	-43.7
EZ	EZ 1	-31.0	-29.2	-29.9	-28.3	-30.0	-30.9	-31.1	-29.1	-29.8	-33.3	-32.1	-28.3	-29.8	-28.3	-29.5	-28.9
	EZ 2	-36.3	-36.3	-36.8	-34.8	-36.4	-36.9	-36.4	-33.2	-36.3	-37.2	-35.5	-34.4	-36.4	-37.0	-37.2	-34.8
	EZ 3	-35.2	-32.9	-36.3	-32.8	-33.1	-33.2	-33.4	-35.0	-34.4	-35.5	-36.3	-34.9	-36.2	-37.0	-36.9	-34.5
	EZ 4	-44.9	-43.7	-45.0	-42.8	-43.3	-43.0	-44.0	-41.0	-43.9	-42.8	-44.5	-43.0	-44.3	-44.0	-43.9	-42.2

	Binder	Data: ABCD Strain Jump at Fracture, ìå															
Lab	ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
WI	EZ 1	39.7	17.0	97.5	33.8	47.9	26.0	17.0	19.9	32.3	40.4	27.2	21.0	46.3	97.7	64.3	65.0
	EZ 2	54.0	36.7	38.6	36.7	42.1	37.8	44.7	31.4	58.8	20.4	26.3	33.4	36.6	47.2	32.6	49.9

	EZ 3	18.5	45.6	25.4	21.3	30.6	41.0	24.9	26.0	45.6	25.1	27.7	38.8	31.2	47.8	29.5	18.4
	EZ 4	62.8	29.3	28.6	47.9	74.9	65.5	43.1	55.4	59.8	35.9	35.4	28.2	54.9	40.4	31.2	35.8
NC	EZ 1	32.6	25.2	18.9	12.0	25.4	29.6	12.8	8.8	31.4	14.0	8.1	23.6	33.8	29.3	25.7	40.9
	EZ 2	7.1	14.7	8.9	9.8	21.5	16.6	13.4	28.1	9.9	9.1	28.4	33.7	8.6	9.6	13.4	43.0
	EZ 3	12.0	17.7	22.8	22.0	18.9	34.4	28.7	34.9	32.0	30.0	8.4	23.8	39.1	18.7	23.8	29.2
	EZ 4	31.4	11.6	28.4	17.1	20.7	38.4	18.1	18.0	14.3	16.1	21.1	12.7	21.1	15.6	10.5	16.5
EZ	EZ 1	37.0	39.7	29.4	31.2	39.4	47.9	23.9	35.2	30.6	37.5	35.2	29.8	25.5	27.8	20.8	26.8
	EZ 2	42.2	28.6	34.8	34.8	40.2	49.7	31.4	32.9	38.7	44.8	25.9	35.5	40.5	41.8	31.2	40.5
	EZ 3	30.5	16.3	20.4	13.6	26.2	11.5	9.1	26.4	24.3	27.4	23.2	23.3	34.0	33.1	18.9	24.6
	EZ 4	64.8	49.9	48.3	38.5	48.7	52.3	34.5	33.9	46.6	46.4	41.4	44.4	52.4	51.6	35.7	41.8

Table 14. Summary of F Values for All Laboratories, All Materials, and All Factors (ABCD Cracking Temperature)

Lab	Asphalt	Std. Dev. (RMSE)	Cooling Rate	Protrusion	Over Trim	Lubrication	Turn Table	Cold Joint	Condition Time
	EZ 1	2.34	NS	NS	NS	NT	NS	NS	NS
WI	EZ 2	0.83	NS	NS	58.27	NT	NS	NS	1432.82
	EZ 3	1.93	NS	NS	NS	NT	NS	NS	NS
	EZ 4	1.87	8.36	NS	36.40	NT	NS	NS	NS
	EZ 1	1.87	NS	16.51	NS	NT	NS	NS	NS
NC	EZ 2	1.91	NS	13.75	NS	NT	NS	NS	NS
	EZ 3	1.54	NS	27.57	NS	NT	NS	NS	NS
	EZ 4	2.49	NS	NS	NS	NT	NS	NS	NS
	EZ 1	1.39	NS	NS	NS	NT	NS	NS	NS
EZ	EZ 2	0.57	NS	82.70	18.82	NT	NS	122.44	NS
	EZ 3	1.65	NS	NS	NS	NT	NS	NS	NS
	EZ 4	0.63	NS	NS	133.54	NT	NS	7.44	NS

NS: not significant at 95% confidence level
NT: not tested
Critical F Statistics at 95% confidence level = 5.59

Table 15. Analysis of Variance of Ruggedness Test including Laboratories and Binder Types (Cracking Temperature)

Dependent Variable: ABCD Cracking Temp

Source	Type III SS	df	Mean Square	F	Sig.
Corrected Model	4860.693(a)	11	441.881	130.313	.000
Intercept	263551.470	1	263551.470	77722.475	.000
Lab	365.832	2	182.916	**53.943**	**.000**
Asphalt	4434.398	3	1478.133	**435.908**	**.000**
Cool Rate	3.825	1	3.825	1.128	.290
Protrusion	10.407	1	10.407	3.069	.082
Over Trim	39.513	1	39.513	**11.652**	**.001**
Turn Table	3.440	1	3.440	1.014	.315
Cold Joint	1.860	1	1.860	.549	.460
Condition Time	1.418	1	1.418	.418	.519
Error	610.367	180	3.391		

Total	269022.530	192			
Corrected Total	5471.060	191			

a R Squared = .888 (Adjusted R Squared = .882)

Linear regression can provide quantified measures of significant variables, in terms of factor adjusted mean differences as shown in Table 16. In comparison to EZ Asphalt lab data, the average ABCD cracking temperatures determined by NC lab is 0.019°C warmer and those WI is 2.9°C lower. In comparison to EZ 1 binder (PG 64-16), EZ 2 (PG 70-22M) showed 6.0°C lower ABCD cracking temperatures on average; 5.8°C and 13.5°C lower for EZ 3 (PG 58-28) and EZ 4 (PG 63-34M), respectively. Figure 7 shows the average effects of laboratory and binder type. 'Over Trim' by 0.8mm resulted in 0.9° C warmer ABCD cracking temperatures on average. All other factors' influence in ABCD cracking temperature was less than 0.50°C and was not statistically significant.

Table 16. Linear Regression of Ruggedness Test Results (Cracking Temperature)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B(°C)	Std. Error(°C)	Beta		
1	(Constant)	-30.226	.460		-65.657	.000
	NC	.019	.326	.002	.058	.954
	WI	-2.919	.326	-.258	-8.966	.000
	EZ2	-6.042	.376	-.490	-16.073	.000
	EZ3	-5.825	.376	-.473	-15.497	.000
	EZ4	-13.540	.376	-1.098	-36.021	.000
	CoolRate	-.282	.266	-.026	-1.062	.290
	Protrusion	.466	.266	.044	1.752	.082
	OverTrim	.907	.266	.085	3.414	.001
	TurnTable	.268	.266	.025	1.007	.315
	ColdJoint	-.197	.266	-.018	-.741	.460
	Condition	-.172	.266	-.016	-.647	.519

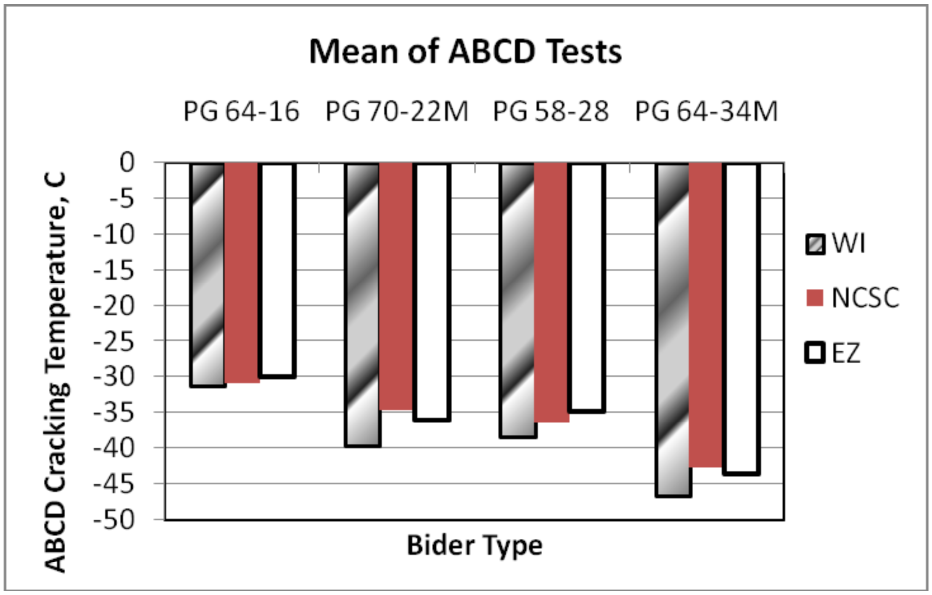

Figure 7. ABCD Ruggedness Test Results (Cracking Temperature); Comparison of Laboratory and Binder Type

4B.2 Strain Jump at Fracture

ABCD strain jump (å) at fracture can be converted into the fracture stress of the asphalt binder ($ó_f$) as follows:

$$ó_f = (K)\ å \cdot E_{ABCD} \cdot A_{ABCD}/A_{binder} \qquad (\text{or} \quad ó_f = 147\ å\ \text{kPa})$$

where,

K = stress concentration factor, 2.02
E_{ABCD} = Young's modulus of ABCD ring, 140 GPa
A_{ABCD} = Cross sectional area of ABCD ring, 21.0 x 10^{-6} mm^2
A_{binder} = Cross sectional area of asphalt binder, 40.3 x 10^{-6} mm^2

Following ASTM C 1067, data (Table 13) were analyzed and summarized in Table 17. When reviewed for each combination of four asphalt binder types and three laboratories, there are 12 cases as shown. The size of protrusion is the factor affecting test results most significantly (six significant cases). For all four binders tested at the EZ Asphalt laboratory, the effect of protrusion size is significant. Lack of significance for other laboratories may be due to larger overall test variability (within lab).

Table 17. Summary of F Values for All Laboratories, All Materials, and All Factors

Lab	Asphalt	Std. Dev. (RMSE)	Cooling Rate	Protrusion	Over Trim	Lubrication	Turn Table	Cold Joint	Condition Time
	EZ 1	30.74	NS	NS	NS	NT	NS	NS	NS
WI	EZ 2	8.13	NS	NS	NS	NT	NS	NS	**5.99**
	EZ 3	9.97	NS	NS	NS	NT	NS	NS	NS
	EZ 4	11.30	**7.89**	**52.80**	NS	NT	NS	**40.45**	NS
	EZ 1	10.14	NS	NS	NS	NT	NS	NS	NS
NC	EZ 2	9.45	NS	**6.46**	NS	NT	NS	NS	NS
	EZ 3	9.59	NS	NS	NS	NT	NS	NS	NS
	EZ 4	7.77	NS	NS	NS	NT	**8.09**	NS	NS
	EZ 1	6.89	NS	**12.12**	NS	NT	NS	NS	NS
EZ	EZ 2	5.44	NS	**24.35**	NS	NT	NS	NS	NS
	EZ 3	7.46	NS	**7.77**	NS	NT	NS	**7.22**	NS
	EZ 4	5.61	NS	**169.3**	NS	NT	NS	NS	NS

NS: not significant at 95% confidence level
NT: not tested
Critical F Statistics at 95% confidence level = 5.59

In preparation for the Interlaboratory test, the statistical difference between laboratories was also examined and the results are given Table 18. ABCD strain jump at fracture can differentiate asphalt types (F value = 6.68, p-value < 0.001). Among the ruggedness factors, ‘Protrusion’ size and use of ‘Turn Table’ are statistically significant in affecting ABCD strain jump (significance level less than 1%).

Linear regression provides quantified measures of these differences, in terms of factor adjusted mean differences as shown in Table 19. In comparison to EZ Asphalt lab data, the average ABCD strain jump determined by NC lab is 13 ìå lower and that by WI is 5 ìå higher. Increasing the protrusion diameter from 5.84 mm (0.23 in.) to 6.34 mm (0.25 in.) lowered the strain jump at failure by 5 ìå. The use of turntables in sample preparation and handling also lowered the strain jump at failure by 4 ìå. Figure 8 shows the average effects of laboratory and binder type on ABCD strain jump at fracture.

Table 18. Analysis of Variance of Ruggedness Test including Laboratories and Binder Types (Strain Jump)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	17545.530(a)	11	1595.048	11.190	.000
Intercept	194298.025	1	194298.025	1363.055	.000
Lab	11749.674	2	5874.837	**41.214**	**.000**
AC	2857.001	3	952.334	**6.681**	**.000**
CoolRate	410.670	1	410.670	2.881	.091
Protrusion	1346.201	1	1346.201	**9.444**	**.002**
OverTrim	3.521	1	3.521	.025	.875
TurnTable	900.467	1	900.467	**6.317**	**.013**
ColdJoint	269.327	1	269.327	1.889	.171
Condition	8.670	1	8.670	.061	.805
Error	25658.284	180	142.546		
Total	237501.840	192			
Corrected Total	43203.815	191			

a R Squared = .406 (Adjusted R Squared = .370)

Table 19. Linear Regression of Ruggedness Test Results (Strain Jump)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	40.078	2.985		13.427	.000
	NC	**-13.270**	2.111	-.417	**-6.288**	**.000**
	WI	**5.336**	2.111	.168	**2.528**	**.012**
	EZ2	-1.798	2.437	-.052	-.738	.462
	EZ3	-6.796	2.437	-.196	-2.789	.006
	EZ4	3.940	2.437	.114	1.617	.108
	CoolRate	2.925	1.723	.097	1.697	.091
	Protrusion	**-5.296**	1.723	-.177	**-3.073**	**.002**
	OverTrim	-.271	1.723	-.009	-.157	.875
	TurnTable	**-4.331**	**1.723**	-.144	**-2.513**	**.013**
	ColdJoint	-2.369	1.723	-.079	-1.375	.171
	Condition	.425	1.723	.014	.247	.805

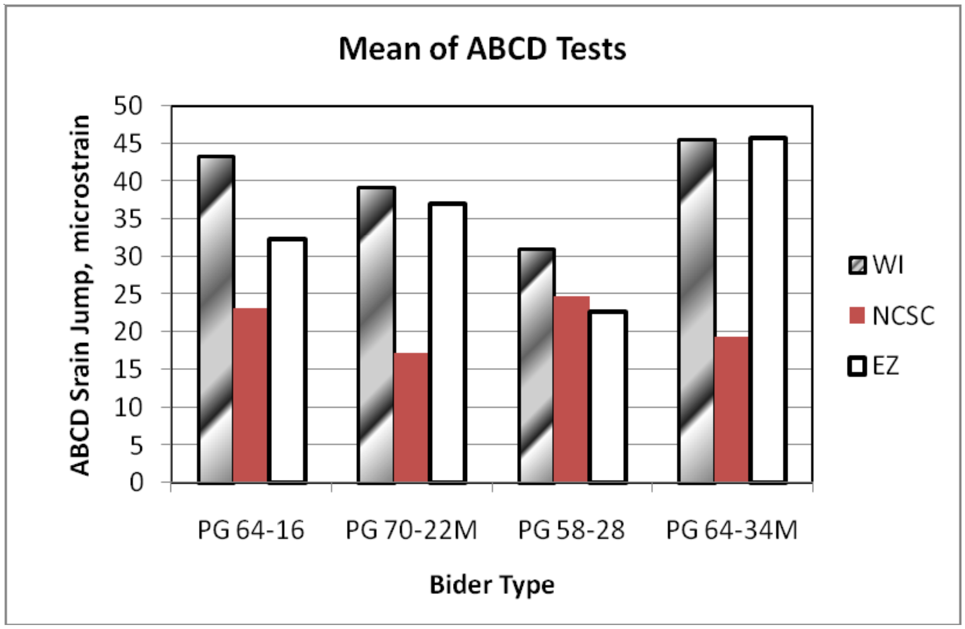

Figure 8. ABCD Ruggedness Test Results (Strain Jump); Comparison of Laboratory and Binder Type

The analysis of the ruggedness test shows that ABCD testing is

1. Able to differentiate different asphalt binders in terms of their low temperature cracking potential and strength (strain jump at failure).
2. At each laboratory, the ABCD test results were reproducible.

However, as the statistics above indicate, there was significant variability among laboratories. Therefore, the EZ Asphalt Technology laboratory performed investigative testing which resulted in modifying the ABCD test procedure. Then, additional samples of the binders (EZ1, EZ2, EZ3, and EZ4) were sent to the NC and WI labs, and those labs conducted supplemental tests to validate the updated ABCD test procedure.

4C. Supplemental Test (Pilot Interlaboratory Study)

The ruggedness testing focuses on “within Lab” variability not “between Lab” variability. Factors affecting “between Lab” may or may not influence “within Lab” variability.

As discussed in the previous section, over-trimming and the size of the protrusion diameter need to have tighter controls than other factors since they were determined to statistically affect ABCD cracking temperatures. Avoiding over-trimming depends on operator expertise while protrusion diameter is fixed by the type of mold provided to each lab. The harder-to-control factor of operator expertise is further addressed in this section which describes supplemental tests which have been conducted to address this issue.

In preparation for the Interlaboratory Study planned for Phase II, some of the ruggedness data performed under conditions close to the normal ABCD tests were reviewed (data #3, #7, #11, and #15). For these data, tests were performed with the regular protrusion mold and even trimming. For data #3 and #11 no turntable was used and samples were cooled for 50 min at 0℃ prior to trimming. For data #7 and #15, turntables were used and samples were cooled for 20 min at 0℃ prior to trimming. These data are given in Table 20 and 21 for ABCD cracking temperature and strain jump respectively.

The ASTM ruggedness procedure ignores interactions among variables. The resulting statistics also assume no interaction. In the ABCD ruggedness testing, there appear to be very significant variations in ABCD test proficiency among operators. The operator at the EZ Asphalt lab has performed the ABCD test for ten months since February 2008. Operators at the other two labs had no prior experience with ABCD; while one of them (NC) had many years of professional experience in asphalt material testing, the other (WI) started asphalt testing 1.5 years ago as he started graduate study. The level of operator experience is an important factor in explaining the ABCD ruggedness test results. Among laboratories, there was significant variability.

Table 20. Original Ruggedness Results for Cracking Temperature.

Binder ID	**Lab**	**ABCD Cracking Temperature, C**						**Lab Avg Range (Max-Min)**
		Data #3	**Data #7**	**Data #11**	**Data #15**	**Mean**	**St Dev**	
EZ 1	**WI**	-30.1	-33.8	-32.9	-30.8	**-31.9**	**1.7**	2.1
	NC	-30.3	-28.7	-27.4	-32.9	**-29.8**	**2.4**	
	EZ	-29.9	-32.1	-31.1	-29.5	**-30.7**	**1.2**	
EZ 2	**WI**	-39.3	-38.4	-42.9	-42.1	**-40.7**	**2.2**	5.8
	NC	-35.8	-34.9	-33.5	-35.2	**-34.9**	**1.0**	
	EZ	-36.8	-35.5	-36.4	-37.2	**-36.5**	**0.7**	
EZ 3	**WI**	-37.9	-40.1	-38.4	-40.8	**-39.3**	**1.4**	4.5
	NC	-36.5	-31.8	-35.8	-35.1	**-34.8**	**2.1**	

	EZ	-36.3	-36.3	-33.4	-36.9	**-35.7**	**1.6**	
EZ 4	**WI**	-47.3	-47.0	-48.8	-46.5	**-47.4**	**1.0**	4.9
	NC	-45.3	-41.9	-39.6	-43.1	**-42.5**	**2.4**	
	EZ	-45.0	-44.5	-44.0	-43.9	**-44.4**	**0.5**	

Table 21. Original Ruggedness Results for Strain Jump.

Binder ID	**Lab**	**ABCD Cracking Temperature, C**						**Lab Avg Range (Max-Min)**
		Data #3	**Data #7**	**Data #11**	**Data #15**	**Mean**	**St Dev**	
EZ 1	**WI**	97.5	27.2	17.0	64.3	**51.5**	**36.8**	35.1
	NC	18.9	8.1	12.8	25.7	**16.4**	**7.6**	
	EZ	29.4	35.2	23.9	20.8	**27.3**	**6.3**	
EZ 2	**WI**	38.6	26.3	44.7	32.6	**35.6**	**7.9**	19.5
	NC	8.9	28.4	13.4	13.4	**16.0**	**8.5**	
	EZ	34.8	25.9	31.4	31.2	**30.8**	**3.7**	
EZ 3	**WI**	25.4	27.7	24.9	29.5	**26.9**	**2.1**	9.0
	NC	22.8	8.4	28.7	23.8	**20.9**	**8.7**	
	EZ	20.4	23.2	9.1	18.9	**17.9**	**6.1**	
EZ 4	**WI**	28.6	35.4	43.1	31.2	**34.6**	**6.3**	20.5
	NC	28.4	21.1	18.1	10.5	**19.5**	**7.4**	
	EZ	48.3	41.4	34.5	35.7	**40.0**	**6.3**	

To develop a better test procedure, additional tests were conducted at the EZ Asphalt lab to investigate the effect of cooling at room temperature before trimming (rather than cooling at 0℃). EZ Asphalt also ran tests to investigate the effect of rotating the ABCD ring after trimming to reduce variation in the strain jump. After trimming, rotating the ABCD ring about 5 to 30 degrees and back breaks any bond that was formed between the ABCD ring and the binder. While lubrication is the major factor allowing the binder to contract freely against the ring, rotating the ring further reduces friction between the binder and ring. Cooling at room temperature for one hour resulted in much easier trimming than at 0℃, thus more consistent sample preparation when investigated by having a new person conduct tests at the EZ Asphalt lab.

Over the last several years, Dr. Kim investigated room temperature trimming for various time periods. The duration of cooling was not determined to be a critical variable so long as it was at least 45 minutes. From Dr. Kim's historical work with ABCD cooling times, one hour was selected.

Rotating the ring reduced the standard deviation among the EZ Asphalt samples. EZ Asphalt then tested all four binders used in the ruggedness test again but with room temperature cooling, four turntables, ring rotation, and in four identical standard molds. The standard molds all had the standard protrusion diameter and did not have an indentation (the indentation used in the ruggedness molds simulated over-trimming). These standard tests were all run at a cooling rate of 20°C per hour (rather than 18 and 22°C/hr in the original ruggedness tests).

While investigating the effect of ring rotation and room temperature cooling at the EZ Asphalt lab, a video was received from the WI lab showing its trimming technique.The WI trimming does not agree with the trimming method shown in EZ Asphalt's training video. The WI trimming method tends to push excess binder back into the annulus rather than removing the excess. EZ Asphalt surmised that the WI trimming method could easily account for the higher standard deviations among their samples as well as the deviations between the WI average cracking temperatures and those of NC and EZ Asphalt.

As a result of viewing the WI video, EZ Asphalt asked WI to test an EZ3 binder using the trimming method shown in the EZ Asphalt video. Their results were much better. EZ Asphalt then mailed both the NC and WI labs additional cans of all four binders. Then NC and WI tested all four binders using the four standard identical molds (standard protrusion, no indent), four turntables, room temperature cooling for one hour, ring rotation, and cooling rate of 20ºC/hr (and for WI, the proper trimming method). The results of the supplement tests are given in Tables 22 and 23 for cracking temperature and strain jump. respectively. By using the standard procedure (and proper WI trimming), the standard deviations of “within lab” measurements as well as between lab variability became smaller for both ABCD cracking temperature and strain jump. The "Max-Min" values in the Tables became smaller. The "Max-Min" value for a binder was computed by subtracting the minimum mean value for the binder from the maximum mean value for the binder. For instance in Table 22 for EZ3, "Max-Min" = 38.2-35.2=2.1ºC (other values may not be exact due to round-off when the table was imported from Excel). This value represents the variation among the three different labs for the same binder. The standard procedure (and proper WI trimming) reduced the EZ1 "Max-Min" from 2.1ºC to 1.5ºC, EZ2 from 5.8ºC to 1.3ºC, EZ3 from 4.5ºC to 3.0ºC and EZ4 from 4.9ºC to 1.1ºC.

As shown in Tables 24 and 25, EZ Asphalt lab results (most experienced ABCD operator) were least affected by changing the test procedure and WI lab results (least experienced ABCD operator) were most affected. Polymer modified binder results (EZ2 and EZ4) improved more than unmodified binder results.

Table 22. ABCD Supplement Test Results for Cracking Temperature. Standard Procedure.

Binder ID	Lab	ABCD Cracking Temperature, C						Lab Avg Range (Max-Min)
		Rep #1	Rep #2	Rep #3	Rep #4	Mean	St Dev	
EZ 1	**WI**	-32.2	-31.6	-31.1	-31.7	**-31.7**	**0.4**	1.5
	NC	-30.5	-26.9	-31.4	-31.7	**-30.1**	**2.2**	
	EZ	-32.3	-29.5	-31.1	-30.9	**-30.9**	**1.2**	
EZ 2	**WI**	-37.5	-38.6		-37.1	**-37.7**	**0.7**	1.3
	NC	-37.0	-36.2	-34.8	-37.8	**-36.5**	**1.3**	
	EZ	-36.5	-36.7	-37.7	-35.6	**-36.6**	**0.8**	
EZ 3	**WI**	-36.1	-40.4	-36.9	-39.3	**-38.2**	**2.0**	3.0
	NC	-35.5	-36.6	-34.8	-33.8	**-35.2**	**1.2**	
	EZ	-36.2	-36.9	-35.8	-37.7	**-36.6**	**0.8**	
EZ 4	**WI**	-43.1	-43.5	-42.8	-44.5	**-43.5**	**0.8**	1.1
	NC	-46.5	-43.9	-42.6	-45.1	**-44.5**	**1.7**	
	EZ	-44.7	-43.7	-43.2	-44.1	**-43.9**	**0.6**	

Table 23. ABCD Ruggedness Supplement Test Results for Strain Jump. Standard Procedure.

Binder ID	Lab	ABCD Cracking Temperature, C						Lab Avg Range (Max-Min)
		Data #3	Data #7	Data #11	Data #15	Mean	St Dev	
EZ 1	**WI**	33.1	30.7	21.3	36.5	**30.4**	**6.5**	10.5
	NC	25.4	18.3	32.4	29.0	**26.3**	**6.0**	
	EZ	43.3	38.0	28.0	37.7	**36.7**	**6.4**	
EZ 2	**WI**	17.9	36.7		30.9	**28.5**	**9.7**	6.9
	NC	35.8	37.3	32.5	21.1	**31.7**	**7.3**	
	EZ	37.9	42.8	29.3	28.1	**35.4**	**7.1**	
EZ 3	**WI**	13.1	43.5	20.5	33.6	**27.7**	**13.6**	8.8
	NC	17.7	29.1	17.0	23.4	**21.8**	**5.6**	
	EZ	31.1	33.7	19.1	38.7	**30.7**	**8.3**	
EZ 4	**WI**	29.3	47.7	22.1	25.9	**31.2**	**11.4**	11.0
	NC	30.0	36.2	49.2	32.9	**37.1**	**8.4**	
	EZ	54.5	42.9	28.7	42.8	**42.2**	**10.5**	

Table 24. Difference (Ruggedness – Standard) in ABCD Cracking Temperature caused by changing trimming procedure

		Asphalt Binder				Max-Min (C)
		EZ1	EZ2	EZ3	EZ4	
Lab	WI	-0.2	-3.0	-1.1	-3.9	3.7
	NC	-0.3	1.6	0.4	2.1	2.4
	EZ	0.3	0.2	0.9	-0.4	1.4

Table 25. Difference (Ruggedness – Standard) in ABCD strain jump caused by changing trimming procedure

		Asphalt Binder				Max-Min (µå)
		EZ1	EZ2	EZ3	EZ4	
Lab	WI	21.1	7.1	-0.8	3.3	21.9
	NC	-9.9	-15.7	-0.9	-17.6	16.7
	EZ	-9.4	-4.6	-12.8	-2.2	10.5

Analysis of variance (ANOVA) in Table 26 reveals that the ABCD test procedure used in the original ruggedness test caused “laboratory” to be a very significant factor affecting ABCD cracking temperatures (p-value < 0.01). This means that ABCD cracking temperatures for the same samples determined at three laboratories are significantly different. Of all variability in ABCD cracking temperature, 81.3% (1178.4/1449.3) was due to the difference in asphalt binders and 10.9% (157.8/1449.3) was due to laboratories. When the new ABCD test procedure (cooling to room temperature prior to trimming, and ring rotation) was used in supplemental ruggedness tests, the variability caused by laboratories was significantly reduced and became insignificant (p-value > 0.05) as shown in Table 27. Of all variability in ABCD cracking temperature using the new procedure, 92.3% of the variability was due to the difference in asphalt binders and only 1.0% was due to laboratories.

As shown in Tables 28 and 29, by changing ABCD test procedure, the effects of laboratories on ABCD strain jump at fracture were significantly reduced (from p-value <0.01 to p-value = 0.04), and the effect of the asphalt binder became significant (from p-value = 0.24 to p-value = 0.04). Figures 9 and 10 also show the improved "between lab" variation.

Table 26 Analysis of Variance (ANOVA): The effect of the old trimming procedure (used in original ruggedness test) on ABCD cracking temperature.

Dependent Variable: Tcr (Old Trim)

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	1336.210[a]	5	267.242	99.230	.000
Intercept	67028.327	1	67028.327	24888.313	.000
Lab	**157.841**	**2**	**78.921**	**29.304**	**.000**
Binder	**1178.369**	**3**	**392.790**	**145.847**	**.000**
Error	113.113	42	2.693		
Total	68477.650	48			
Corrected Total	1449.323	47			

a. R Squared = .922 (Adjusted R Squared = .913)

Table 27 Analysis of Variance (ANOVA): The effect of new trimming procedure (used in supplemental test) on ABCD cracking temperature.

Dependent Variable: Tcr (New Trim)

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	1039.126[a]	5	207.825	114.331	.000
Intercept	64593.220	1	64593.220	35534.799	.000
Lab	**10.858**	**2**	**5.429**	**2.987**	**.062**
Binder	**1027.985**	**3**	**342.662**	**188.509**	**.000**
Error	74.528	41	1.818		
Total	65834.607	47			
Corrected Total	1113.654	46			

a. R Squared = .933 (Adjusted R Squared = .925)

Table 28 Analysis of Variance (ANOVA): The effect of the old trimming procedure (used in original ruggedness test) on ABCD strain jump.

Dependent Variable: Jump (Old Trim)

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	3632.440[a]	5	726.488	4.261	.003
Intercept	37940.630	1	37940.630	222.538	.000
Lab	**2880.543**	**2**	**1440.271**	**8.448**	**.001**
Binder	**751.897**	**3**	**250.632**	**1.470**	**.236**
Error	7160.600	42	170.490		
Total	48733.670	48			
Corrected Total	10793.040	47			

a. R Squared = .337 (Adjusted R Squared = .258)

Table 29 Analysis of Variance (ANOVA): The effect of new trimming procedure (used in supplemental test) on ABCD strain jump.

Dependent Variable: Jump (New Trim)

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	1089.847[a]	5	217.969	3.118	.018
Intercept	46782.101	1	46782.101	669.287	.000
Lab	**470.048**	**2**	**235.024**	**3.362**	**.044**
Binder	**619.209**	**3**	**206.403**	**2.953**	**.044**
Error	2865.833	41	69.898		
Total	50980.317	47			
Corrected Total	3955.680	46			

a. R Squared = .276 (Adjusted R Squared = .187)

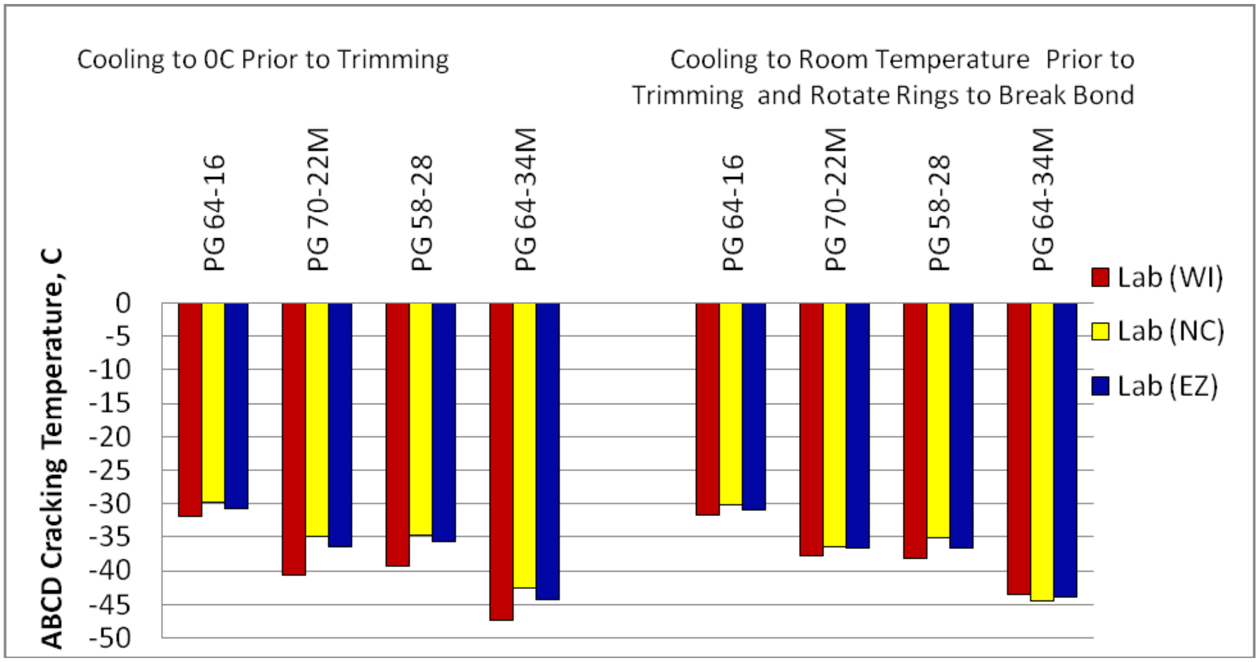

Figure 9. Effects of Sample Preparation Procedures on ABCD Cracking Temperature

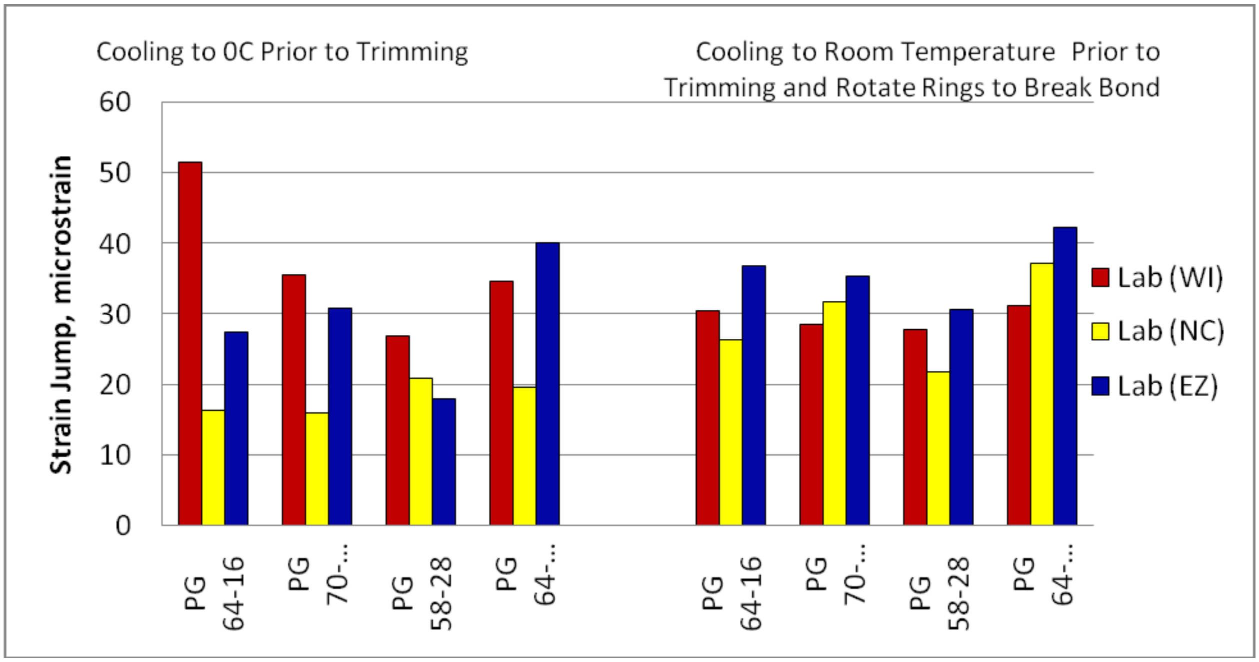

Figure 10. Effects of Sample Preparation Procedures on Strain Jump

4D. Survey of Ruggedness Participants

North Central Superpave Center and University of Wisconsin - Madison completed surveys evaluating their experiences with ABCD in the ruggedness testing and pilot interlaboratory testing. The survey was designed by EZ Asphalt and consisted of 23 questions rating aspects such as pouring, trimming, connecting wires, and running the software on a scale of 1 to 5 with 1 being poorest and 5 being highest rating. In all the questions, a response of 5 would be the most favorable for the ABCD. NC and WI survey results yielded averages of 3.9 and 4.3, respectively. NC was most critical of the difficulty in constructing the pouring spout and computer problems. WI was most critical of the computer requiring a re-start after every test and the pourability of the binders. EZ Asphalt will work to solve these problems. Complete survey results for NC and WI appear in Appendix B.

Conclusion

The ABCD has been evaluated in Phase 1 for refinement of test procedures, field validation of the ABCD, refinement of equipment and analysis software, and ruggedness testing. Throughout the year of Phase 1 investigations, the ABCD device was improved to the point where it only must now undergo Interlaboratory testing for it to be a saleable device.

In Phase 1, the silicone mold was modified, the cooling rate was optimized, and turntables were incorporated. Many binders were tested for continuous improvement of the ABCD. Ruggedness testing is an important aspect of bringing a new test device to market. Successful ruggedness testing of the ABCD at the North Central Superpave Center, University of Wisconsin - Madison, and EZ Asphalt laboratories showed that the ABCD is ready for Interlaboratory Testing in Phase 2. The ABCD has the potential to save the country significant funds since it provides a direct, consistent, and accurate determination of the cracking temperature and strength of aged, unaged, polymer-modified, and unmodified binders. It provides a cracking temperature that mimics field results more reliably than existing methods and will likely prove to be very economical for the industry.

Appendix B.
Ruggedness Surveys from North Central Superpave Center and University of Wisconsin-Madison

ABCD RUGGEDNESS TESTING - SURVEY

Thank you for participating in the Ruggedness Testing. Please fill out this survey by either bolding or underlining your responses. Comments can be written in non-bolded font. Then email it back to Ken Edwards as an attachment at LMNO@LMNOeng.com . If questions, please call Ken at 740/707-2614 or Dr. Kim (skim@EZAsphaltTechnology.com) at 740/707-6817.

Laboratory: EZ Asphalt **NC Superpave Center** University of Wisconsin

Please answer the following questions on a scale of 1 to 5 with 1 being do not agree and 5 being strongly agree. Feel free to add comments.

Do not agree
Strongly agree

Setting up the computer, cooling chamber,
and data collection that arrived at our lab was easy: 1 2 3 **4** 5

Comment:___**I did not set it up initially, but it appears to be straightforward**_________

Constructing the pouring spout was easy: **1** 2 3 4 5

Comment: **Nope! I found the spout and holder assembly very cumbersome, and did not use it, per Dr. Kim's suggestion during training. Had better control on the pour without it.**

Pouring the binder was easy: 1 2 3
4 5

Comment:____**It was easy for unmodified binders**___________________________

I always started pouring in the vicinity of the protrusion: 1 2 3 4
5

Comment:____

Some binders poured more easily than others: 1 2 3 **4** 5

Comment:______**Yes, modified binders were harder to pour, as expected**____________

Creating the cold joint was easy: 1 2 3 **4** 5

Comment:_____**Yes, it was**____

I was good at monitoring the time that the samples were in the 0^{o}C chamber: 1 2 3 4 **5**

Comment:____

Some binders were harder to trim than others: 1 2 3 **4** 5

Comment:___**The modified binders formed strings and did not cut/trim as easily**_____

Keeping the spatula hot aided trimming: 1 2 3 4 **5**

Comment:____

It was easy to connect the wires to the samples: 1 2 3 4 **5**

Comment:____

It was easy to run the software: 1 2 3 **4** 5

Comment:____

The computer never locked up: **1** 2 3 4 5

Comment:__**Had numerous problems with the old laptop (software) and the new one. Errors appeared to be random, no pattern to them even if the same procedure was adopted every day.**__

It was easy to run the macro: 1 2 3 4 **5**

Comment:____

It was easy to disconnect the wires from the samples at the end of the test: 1 2 3 **4** 5

Comment:____

If I had questions, EZ Asphalt was readily available: 1 2 3 4 **5**

Comment:____

The procedure for preparing a sample was easy to follow: 1 2 3 **4** 5

Comment:____

I looked at the video on the EZAsphaltTechnology.com website: **1** 2 3 4 5

Comment**:** **No**____

The ruggedness testing variables were reasonable: 1 2 **3** 4 5

Comment:_____**Maybe need more cooling rates trials**___________________________

The ABCD is a promising method for obtaining binder cracking temperature: 1 2 3 **4** 5

Comment:____

I would like our laboratory to purchase the ABCD test apparatus: 1 2 3 4 5

Comment:_________**See comment below**__________________________________

Complete the following sentence about the ABCD: I wish ________________________________

How does sample preparation and usefulness of the results compare to other binder tests you have run (e.g., Direct Tension Test and Bending Beam Rheometer)?

With ABCD we will not need to run both BBR and DTT if $T_{cracking}$ is the parameter of interest. But some comparative trials using BBR-DTT combination and the ABCD alone are needed on replicate samples to determine if they give “similar” $T_{cracking}$ estimates.

Other comments:

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Laboratory: EZ Asphalt NC Superpave Center **University of Wisconsin**

Please answer the following questions on a scale of 1 to 5 with 1 being do not agree and 5 being strongly agree. Feel free to add comments.

Do not agree
Strongly agree

Setting up the computer, cooling chamber,
and data collection that arrived at our lab was easy: 1 2 3 4 **5**

Comment:____
______

Constructing the pouring spout was easy: 1 2 3 4 **5**

Comment:____
______

Pouring the binder was easy: 1 2 **3**
4 5

Comment: The binder needs to be poured really hot and it is hard to pour 4 samples without needing to heat it in the oven again.

I always started pouring in the vicinity of the protrusion: 1 2 3 4
5

Comment:____
______

Some binders poured more easily than others: 1 2 **3**
4 5

Comment:____
______

Creating the cold joint was easy: 1 2 3
4 **5**

Comment:____
______

I was good at monitoring the time that the samples were in the 0^{o}C chamber: 1 2
3 4 **5**

Comment:____
______

Some binders were harder to trim than others: 1 2 3
4 5

Comment:____
______

Keeping the spatula hot aided trimming: 1 2 3
4 **5**

Comment:____
______

It was easy to connect the wires to the samples: 1 2 3
4 **5**

Comment:____
______

It was easy to run the software: 1 2 3
4 **5**

Comment:____
______

The computer never locked up: 1 **2** 3
4 5

Comment: The computer never locked up, but it was necessary to restart it after every single test, in order to avoid the software to lock up during next test.

It was easy to run the macro: 1 2 3
4 5

Comment:____
______

It was easy to disconnect the wires from the samples at the end of the test: 1 2 3
4 **5**

Comment:____
______

If I had questions, EZ Asphalt was readily available: 1 2 3
4 **5**

Comment:____
______

The procedure for preparing a sample was easy to follow: 1 2 3 **4** 5

Comment:____

I looked at the video on the EZAsphaltTechnology.com website: 1 2 3 4 **5**

Comment:____

The ruggedness testing variables were reasonable: 1 2 3 **4** 5

Comment:____

The ABCD is a promising method for obtaining binder cracking temperature: 1 2 3 **4** 5

Comment:____

I would like our laboratory to purchase the ABCD test apparatus: 1 2 **3** 4 5

Comment:____

Complete the following sentence about the ABCD: I wish more correlation studies with other testing methods will be performed.

How does sample preparation and usefulness of the results compare to other binder tests you have run (e.g. Direct Tension Test and Bending Beam Rheometer)?

Sample preparation is approximately as easy as for other tests. The usefulness of the results has to be investigated, although it looks promising.

Other comments:

Appendix D. ABCD User's Manual

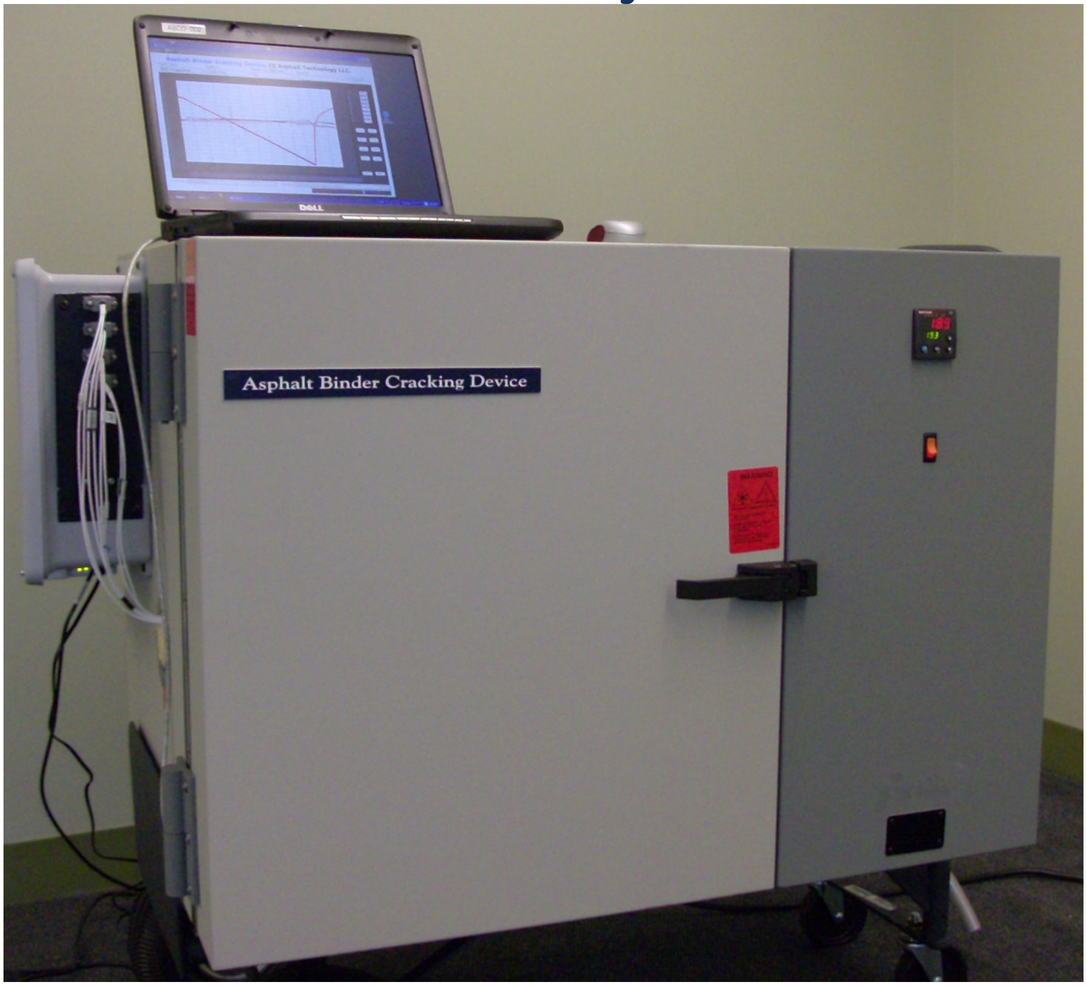
INNOVATIONS IN ASPHALT TESTING

EZASPHALT

TECHNOLOGY, LLC

Asphalt Binder Cracking Device

Detailed Laboratory Procedure



340 W State Street, Unit #2, Suite 142. Athens OH 45701
(740) 597-3230   skim@EZasphaltTechnology.com
http://www.EZasphaltTechnology.com

March 24, 2009

Asphalt Binder Cracking Device (ABCD) Laboratory Procedure

Overview

Thank you for purchasing the ABCD. If you ever have any questions, please call or email us anytime at the contact information listed on the front of this procedure. If we are not in the office, please call or email any of the other cell phone numbers or email addresses that you have been provided. We want to answer your questions. We think you will be very pleased with the design of the ABCD system, and its ability to provide asphalt binder cracking temperatures in a direct manner. This procedure may appear long. We have included a lot of detail so that you understand more than just "what to do". It might be helpful to remove some pages from the 3-ring binder since images are often on different pages from the text descriptions. Hopefully you will agree that the procedure is simple and straight-forward after having prepared and tested about three binders.

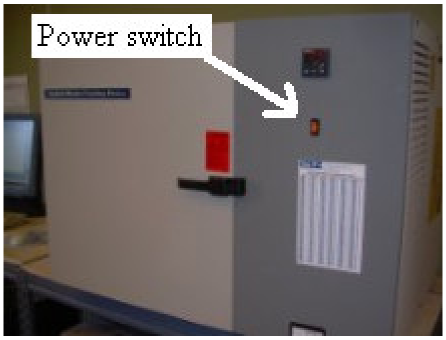
After getting familiar with the procedure through this Detailed Laboratory Procedure, please see the Brief Laboratory Procedure which has suggestions for running multiple tests in an 8-hour work day.

Please see our promotional video at http://www.EZasphaltTechnology.com and procedure video at http://www.EZasphaltTechnology.com/products/abcd/training.php (note procedure video has not been updated as of 3/24/09 to show room temperature cooling in Section 9 of procedure or ring rotation in Section 11 of procedure).

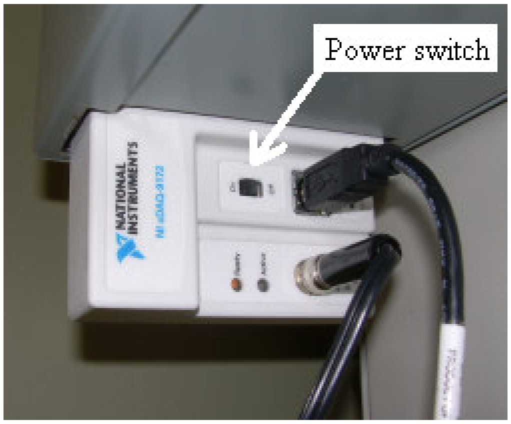
Detailed procedure

1. Safety Precautions
    - 1.1 Latex gloves helpful to keep binder off hands.
    - 1.2 Insulated gloves necessary when holding heated asphalt container and pouring.
    - 1.3 Safety glasses recommended when working with hot binder.

2. Power on Equipment
    - 2.1 Turn on cooling chamber.
    - 2.2 Turn on data collection hardware.
    - 2.3 Computer
        - 2.3.1 Plug USB cable from cooling chamber into computer.
        - 2.3.2 Plug USB cable from data collection hardware into computer.
        - 2.3.3 Power on the computer.
        - 2.3.4 Wait long enough for all software to load and any Vista messages to disappear from the screen (a few minutes).
        - 2.3.5 Double-click Excel 2007 icon on Desktop. This enables the data analysis add-in macro.
        - 2.3.6 If pop-up messages appear anytime with the computer, clicking Cancel is usually appropriate.

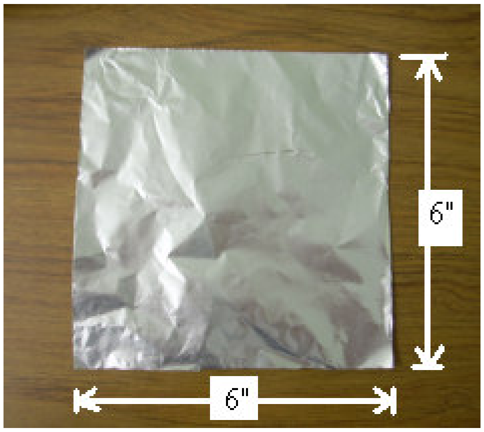


Step 2.1. Cooling chamber. Power switch up in "On" position.

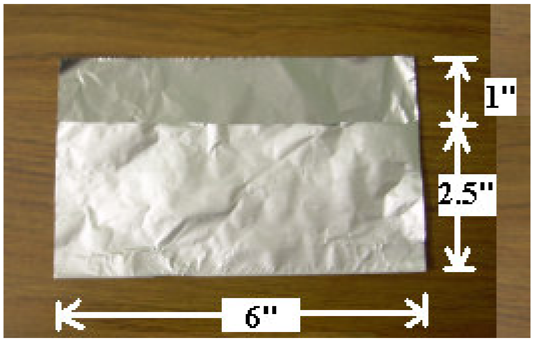


Step 2.2. Data collection hardware. Power switch pushed left in "On" position.

3. Prepare Spout
    3.1 Cut a piece of aluminum foil approximately 6" x 6".
    3.2 Fold the foil so that about 1" is not covered. Does not matter if the shiny or dull side is "up".
    3.3 Rotate the foil 180° (do not flip over).
    3.4 Fold the exposed 1" portion in half.
    3.5 Fold along the joint you just created. Now you should have four thicknesses of foil for about 1/2" and two thicknesses of foil for about 2"
    3.6 Fold a partial diagonal.
    3.7 Fold another partial diagonal. Be sure all folds are creased.
    3.8 You should have formed a 6-sided shape with approximate dimensions shown in the figure.

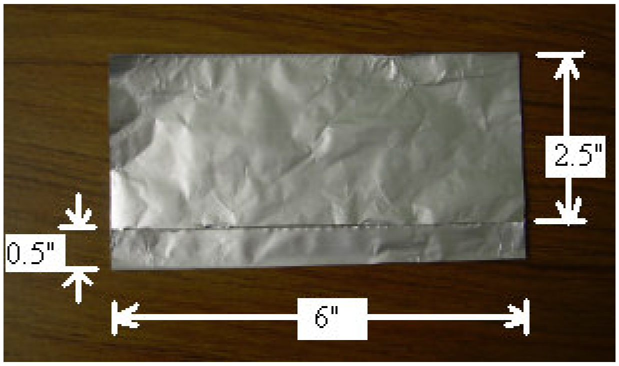


Step 3.1. Aluminum foil.

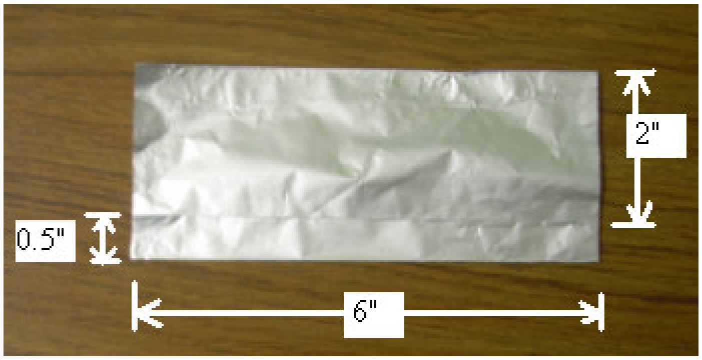


Step 3.2. First crease.

Step 3.3. Same image as Step 3.2 but foil rotated 180 degrees.



Step 3.4. The 1" portion has been folded in half.



Step 3.5. After the fold.

Step 3.6. After folding one diagonal.

Step 3.7. After folding the second diagonal.

4. Mount Spout to Binder Sample Container
    - 4.1 Line up foil on outside of container such that foil covers about 1" of height of the container. The thick portion of foil should line up just below the circumferential indent on the container.
    - 4.2 Smooth the foil around the container indentation for a good seal.
    - 4.3 Mold the foil over the lip of the container for the width of the foil, so binder cannot seep between container and spout.
    - 4.4 Use index finger to form a curved spout. Spout should be bent so that it is horizontal.

Steps 4.1 and 4.2. Line up foil on container.

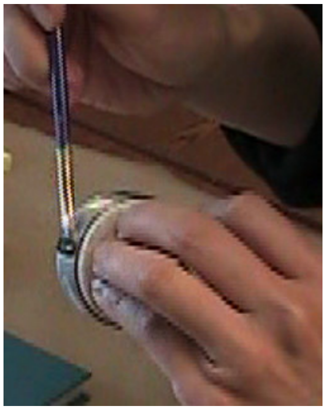
Step 4.3. Mold foil onto container for good seal.

Step 4.4. Form curved spout.

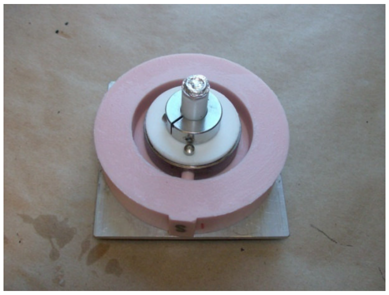
5. Heating
    - 5.1 Set the sample container with attached spout in the pouring ladle (optional) and place into oven.
    - 5.2 Place stirring rod into oven.
    - 5.3 Heat
        - 5.3.1 One hour at 150˚C for unaged binders.
        - 5.3.2 One hour at 160˚C for RTFO binders.
        - 5.3.3 One hour at 170˚C for PAV binders that have not been degassed. Then apply a 25 to 26.5" Hg vacuum (12.5 to 17.5 kPa absolute pressure) for 30 minutes.

6. Lubrication
    - 6.1 Lubricant should be glycerin/talc mixture in 1:1 mass ratio.
    - 6.2 Lubricate four molds (or eight if you have an 8-ring system) using a brush.
        - 6.2.1 Apply lubricant to inside portions of mold where the ring and binder will contact the mold.
        - 6.2.2 Lubricate top of mold to aid cleaning after the test.
    - 6.3 Lubricate four ABCD rings (or eight if you have an 8-ring system) using a brush.
        - 6.3.1 Make sure that the ABCD ring is clear of debris.
        - 6.3.2 Apply lubricant to the metal circumference portion.
        - 6.3.3 Apply lubricant to the plastic top and bottom covers to ease removal of errant binder during trimming and after testing.

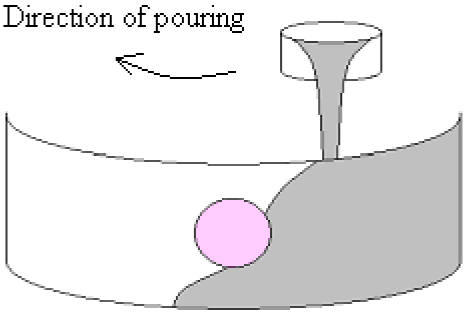

Step 6.2.1. Lubricate mold.


Step 6.3.2. Lubricate ring.

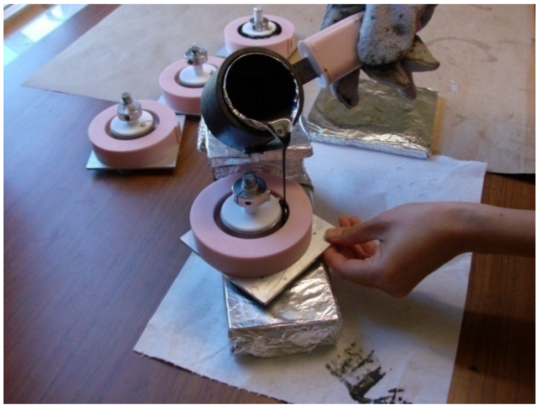
7. Assembly
    7.1 Place all the molds on separate turntables.
    7.2 Set each ABCD ring into a mold.
    7.3 Align the vertical metal dowel post on the ring with the mold protrusion. When moving samples, hold the turntable and avoid holding the mold as this can lead to deformation of asphalt binder specimen


Step 7.3 Completed assembly.

8. Pouring
    8.1 After the binder sample has been heated (and degassed if necessary), remove from oven and stir with heated rod. Gloves are necessary.
    8.2 Starting from a point close to the protrusion, slowly pour the binder into the mold until the binder has completely filled the space directly below the protrusion. Then, slowly pour over the protrusion. (This process minimizes the possibility of trapping air under the protrusion or formation of a cold-joint). Placing the assembly on a pouring stand may aid pouring.



Step 8.2. Pouring.



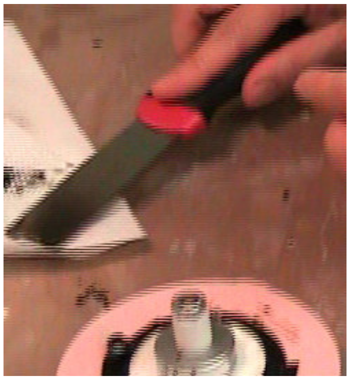
Step 8.2. Pouring.

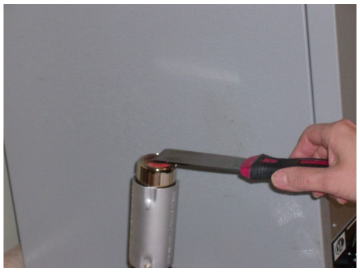
9. Room Temperature Cooling
    - 9.1 After all molds have been filled, let them all sit at room temperature for at least 1 hour.

10. Trimming
    - 10.1 After 1 hour of sitting at room temperature, the samples are ready for trimming.
    - 10.2 Heat a spatula before trimming the samples. The spatula must be sufficiently hot; otherwise, it may stick to the binder and pull it out of shape.
    - 10.3 The heated spatula is held in one hand at an angle between 20° and 45° relative to horizontal while the turntable (and hence the mold/ring/binder) is rotated slowly with the other hand in a direction such that excess binder is removed onto the upper surface of the spatula leaving the remaining binder flush with the upper surface of the mold. The removed binder is discarded periodically by wiping on paper towel. The spatula is re-heated periodically until all of the excess binder is removed. Avoid applying excessive pressure on the spatula or it may depress the flexible mold or over trim the sample. To aid turntable rotation, it is satisfactory to hold both the turntable and top of the ABCD ring with one hand (rather than only holding the turntable) while trimming with the other hand.
    - 10.4 Trim all assemblies.

Step 10.2. Heat spatula.

Step 10.3. Trim binder.





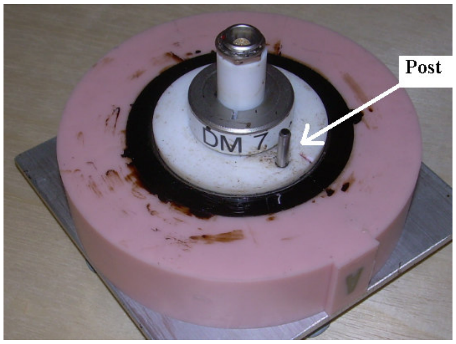
Step 10.3. Clean spatula Step 10.3. Re-heat spatula Step 10.3. Trim
binder.
by wiping on towel.

11. Ring Rotation

11.1 While holding the turntable with one hand (avoid holding the mold if possible), grasp the ring and rotate it between 5 degrees and 30 degrees.

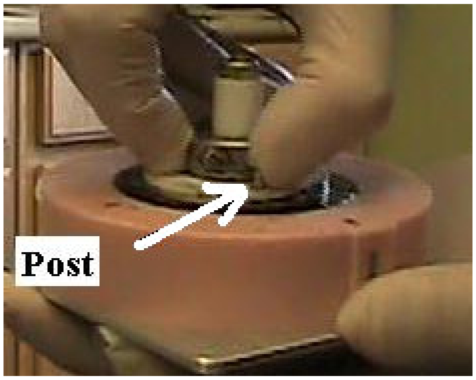
11.2 Then rotate the ring back to its original position. The binder should not rotate. The goal is to break the adhesive bond between the binder and the ring so that the binder will freely contract upon cooling.

11.3 Do this for all assemblies.



Step 11.1. Left hand holding turntable. Initially post lines up with label "V" on mold.

Step 11.1. Right thumb begins to push against post.



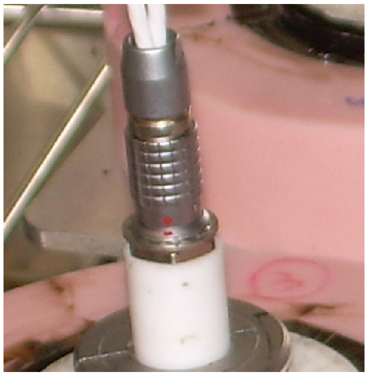
Step 11.1. Post is pushed with right thumb such that ring rotates between 5 and 30 degrees from initial position.

Step 11.1. Ring has been rotated between 5 and 30 degrees from initial position.

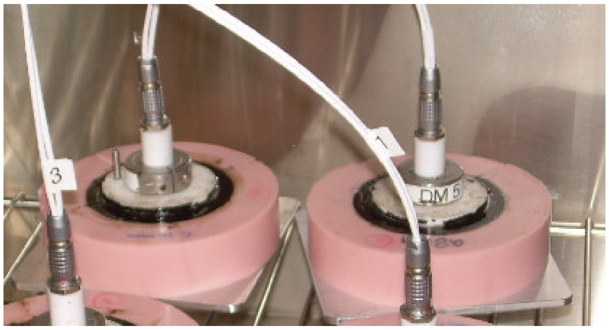
Step 11.2. Post is pushed back by index finger of right hand.

Step 11.2. Rotation completed. Post lines up with label "L" on mold.

12. Place samples into Cooling Chamber
    - 12.1 Place the samples into the cooling chamber.
    - 12.2 Connect the wires to the rings by lining up the red dot on the wire harness with the red dot on the ring.



Step 12.2. Line up red dots on ring and wire harness.



Step 12.2. Assemblies in chamber

13. Software for Data Collection

13.1 From the computer's desktop, double-click the "ABCD" icon. The "DAQ Configuration" screen (tab) should appear. DAQ means Data Acquisition.

Step 13.1. Click on icon.

13.2 DAQ Configuration Tab

13.2.1 Make the screen full size by clicking on the Windows button in the upper right corner or grab the top of the window to bring the entire window into view.

13.2.2 Click the “Check Chamber Communication” button in the lower left corner. If the communication check fails, change the "Chamber Comm Port" from its dropdown menu. Click "Check Chamber Communication" again. Try again until the communication check returns a green light and the words "Communication was Successful" appear.

13.2.3 If not already the default, set the "Data Collection Update Rate" in the upper left corner to 10 seconds. This is the frequency of data collection (minimum value is 1 second).

13.2.4 Check that "Remove Initial Offset" is toggled toward "Yes".

13.2.5 Click the toggle for a 4-ring system or 8-ring system.

13.2.6 Check that "SG1 Scalar", "SG2 Scalar", etc. are set at 1.

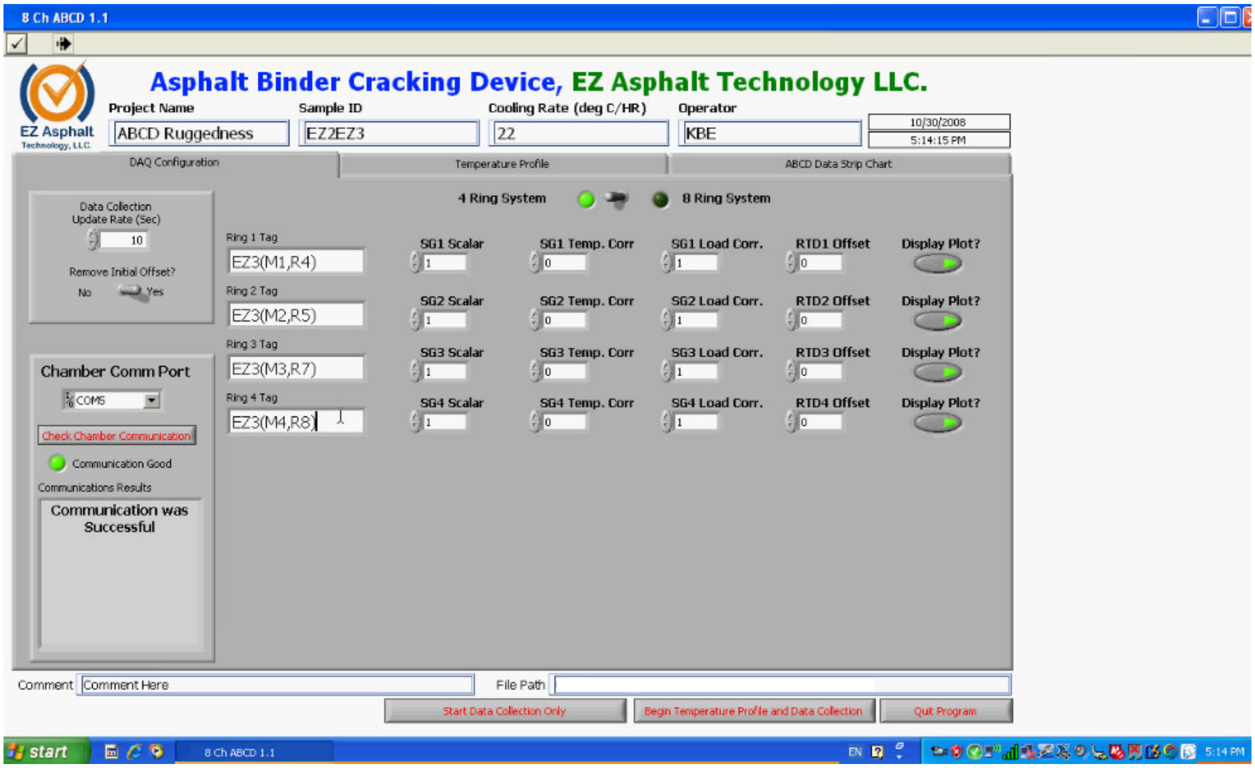
13.2.7 Check that "SG1 Temp. Corr", "SG2 Temp. Corr", etc. are set at 0.

13.2.8 Check that "SG1 Load Corr.", "SG2 Load Corr.", etc. are set at 1.

13.2.9 Check that "RTD1 Offset", "RTD2 Offset", etc. are set at 0.

13.2.10 If you have 4 samples, "Display Plot" should have the green triangle on each toggle. If you only are testing 3 samples, then you can toggle off the 4th sample's plot. Likewise for an 8-ring system.

13.2.11 If desired, edit other text fields such as "Project Name", "Sample ID", "Cooling Rate", "Operator", and "Ring Tag" identifiers. Note that editing the "Cooling Rate" field does not set the cooling rate. It is only used for the title block in the output.



Project Name: ABCD Ruggedness
Sample ID: EZ2EZ3
Cooling Rate (deg C/HR): 22
Operator: KBE
10/30/2008
5:14:15 PM

Data Collection Update Rate (Sec): 10
Remove Initial Offset? No / Yes
Chamber Comm Port: COM5
Communication Good
Communications Results: Communication was Successful

Ring Tag	SG Scalar	SG Temp. Corr	SG Load Corr.	RTD Offset
Ring 1 Tag: EZ3(M1,R4)	SG1 Scalar: 1	SG1 Temp. Corr: 0	SG1 Load Corr.: 1	RTD1 Offset: 0
Ring 2 Tag: EZ3(M2,R5)	SG2 Scalar: 1	SG2 Temp. Corr: 0	SG2 Load Corr.: 1	RTD2 Offset: 0
Ring 3 Tag: EZ3(M3,R7)	SG3 Scalar: 1	SG3 Temp. Corr: 0	SG3 Load Corr.: 1	RTD3 Offset: 0
Ring 4 Tag: EZ3(M4,R8)	SG4 Scalar: 1	SG4 Temp. Corr: 0	SG4 Load Corr.: 1	RTD4 Offset: 0

Comment: Comment Here
File Path:

Step 13.2. DAQ (Data Acquisition) Configuration Tab. Binder being tested is the EZ3 binder. M1 is mold #1, M2 is mold #2 and so on. R4 is ring #4, R5 is ring #5 and so on. Your molds may have letters on them instead of numbers. This particular test was during the ruggedness testing and was conducted at a cooling rate of 22°C/hour instead of the standard 20°C/hour.

13.3 Temperature Profile Tab

13.3.1 Click on the Temperature Profile Tab.

13.3.2 Click the “Get Temperature” button on the left side of the screen (in the Manual Operations section). The display will show the current temperature inside the chamber given by the chamber's temperature sensor. This is a different sensor than the sensors mounted inside each ABCD ring.

13.3.3 Underneath the "Set Temperature Set Point" button (located in the Manual Operations section on the left side of the screen), enter a temperature of 25 degrees C.

13.3.4 Click the "Set Temperature Set Point” button to accept the temperature you just entered.

13.3.5 Click the “Modify Profile” button on the left side of the screen. Clicking this button will change its text to “Accept Changes” and enable the fields below the profile chart to be editable. If the fields are already set as you want them (per the steps below), then you do not need to edit the fields.

13.3.5.1 The Amb Temp (Ambient Temperature) and Time Start fields cannot be changed.

13.3.5.2 Set Point 1 should be entered as 0 (i.e. zero °C). It is the temperature that the chamber will reach after the time set by Time Span 1.

13.3.5.3 Time Span 1 should be 0.5. This is 0.5 hours. It tells the chamber to achieve a temperature of 0C after 0.5 hours.

13.3.5.4 Set Point 2 should be entered as -60 (i.e. -60°C). It is the temperature that the chamber will reach after the additional time set by Time Span 2.

13.3.5.5 Time Span 2 should be entered as 3 (i.e. 3 hours). This is the time interval between Time Span 1 and Time Span 2. The chamber temperature of -60°C will be reached 3.5 hours into the test.

13.3.5.6 Set Point 3 should be entered as 25 (i.e. 25°C). It is the temperature that the chamber will reach after the additional time set by Time Span 3.

13.3.5.7 Time Span 3 should be entered as 0 (i.e. 0 hours). This tells the chamber to instantaneously raise the chamber temperature to 25°C after 3.5 hours.

13.3.5.8 Set Point 4 should be entered as 25 (i.e. 25°C).

13.3.5.9 Time Span 4 should be entered as 1 (i.e. 1 hour).

13.3.5.10 Set Point 5 should be entered as 25 (i.e. 25°C).

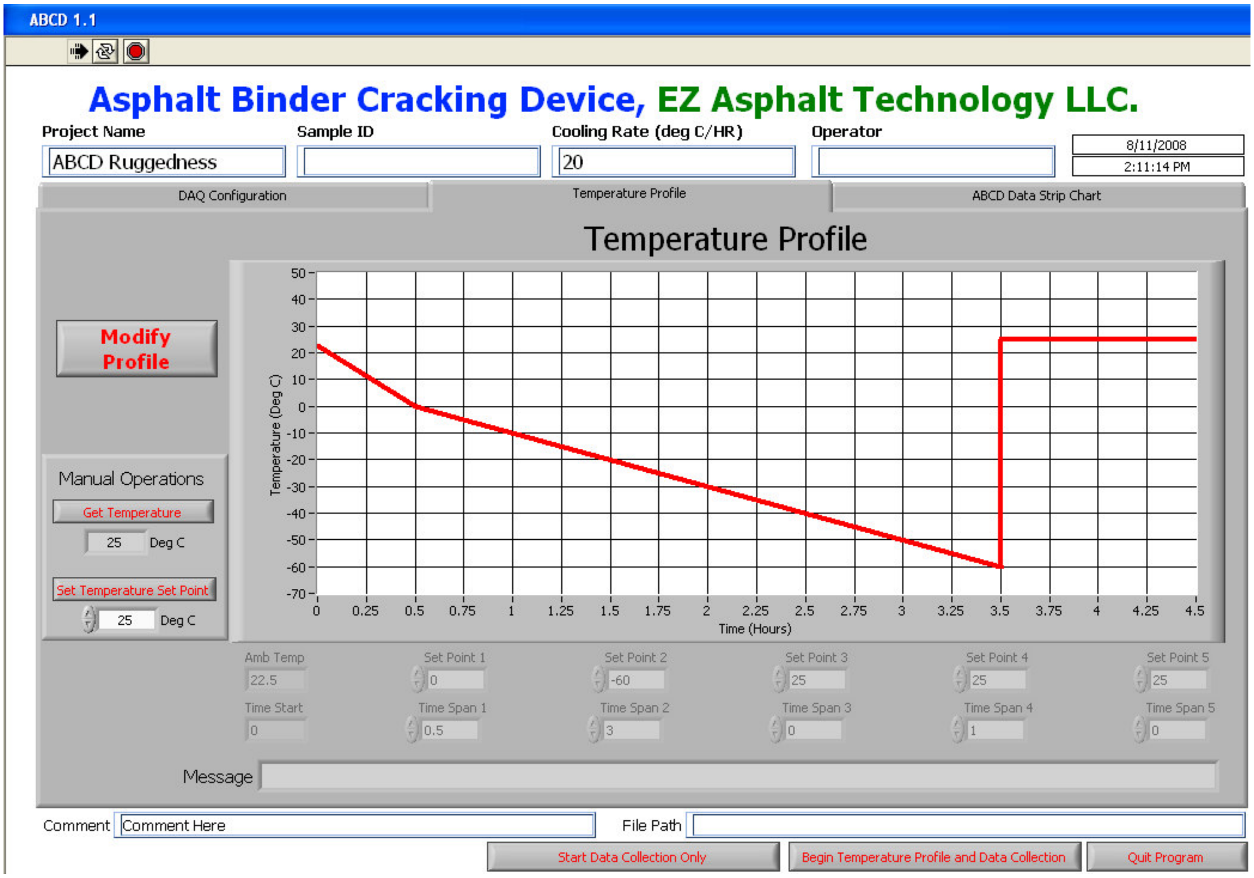
13.3.5.11 Time Span 5 should be entered as 0 (i.e. 0 hours). The chamber is warmed to 25°C after the test in order to reduce condensation on the rings when the chamber door is opened..

13.3.6 Click "Accept Changes" to lock the temperature and time settings you entered in steps 13.3.5.1 through 13.3.5.7. The chamber temperature profile will show graphically on the screen.

13.3.7 Click the “Begin Temperature Profile and Data Collection” button located in the bottom right hand corner.

13.3.7.1 Type a data file name to be saved. The file extension ".xls" will automatically be added to the file name.

13.3.7.2 Click OK and the program will initiate the temperature profile and begin collecting data.



Asphalt Binder Cracking Device, EZ Asphalt Technology LLC.

Project Name: ABCD Ruggedness
Sample ID:
Cooling Rate (deg C/HR): 20
Operator:
8/11/2008
2:11:14 PM

Temperature Profile

Get Temperature: 25 Deg C
Set Temperature Set Point: 25 Deg C

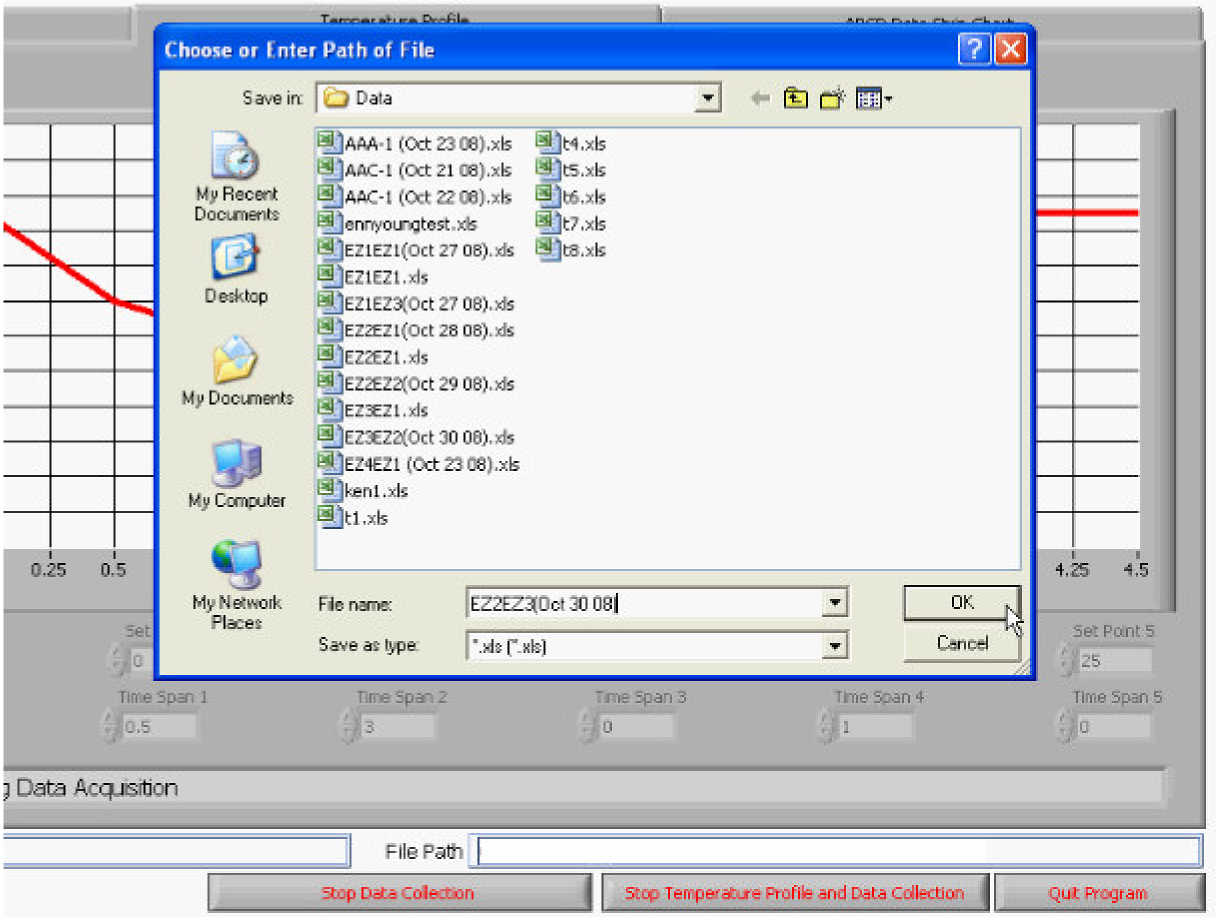
Amb Temp	Set Point 1	Set Point 2	Set Point 3	Set Point 4	Set Point 5
22.5	0	-60	25	25	25

Time Start	Time Span 1	Time Span 2	Time Span 3	Time Span 4	Time Span 5
0	0.5	3	0	1	0

Message:

Comment: Comment Here
File Path:

Step 13.3. Temperature Profile Tab for the standard 20°C/hour cooling rate. (-60°C over a 3 hour period as indicated by Set Point 2 and Time Span 2).



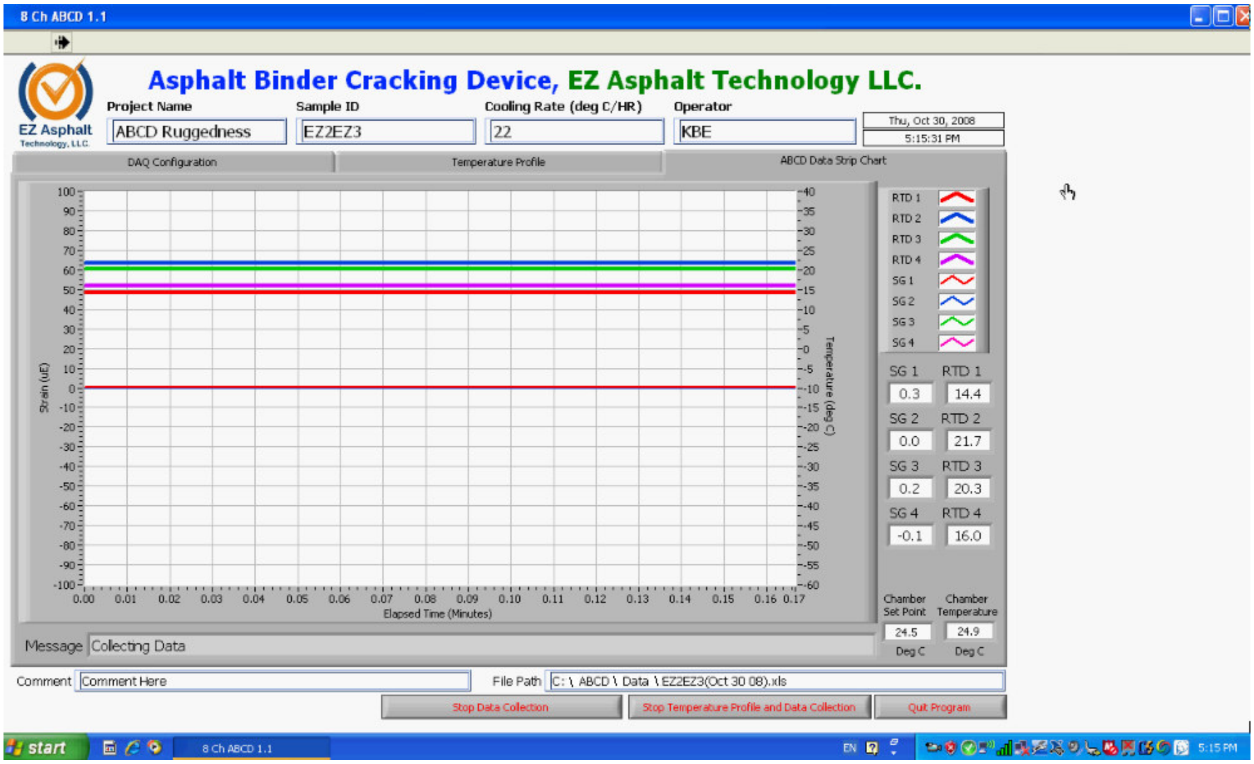
File name: EZ2EZ3(Oct 30 08)

Save as type: *.xls (*.xls)

Step 13.3.7.1. Type file name. The ".xls" extension is automatically put on end of file name.

13.4 Click on the "ABCD Data Strip Chart" tab to monitor data collection.
- 13.4.1 The graphs are updated at the time interval entered in Step 13.2.3 above. The maximum value on the time scale on the x-axis automatically increases as more data is collected.
- 13.4.2 "SG1, RTD1" and so on are Strain Gage and RTD (Resistance Temperature Device) temperature values for each ring.
- 13.4.3 The data ranges on the left and right y-axis scales can be adjusted by clicking the maximum or minimum value and entering a different bound, but the defaults should be satisfactory.
- 13.4.4 The data collection will automatically stop when the temperature profile completes.
- 13.4.5 Stopping the program prior to performing the entire temperature profile.
  - 13.4.5.1 Only done in unusual circumstances.
  - 13.4.5.2 The program can be manually stopped at any time by clicking the “Stop Temperature Profile and Data Collection” button located at the bottom right corner. The data up to that point has already been saved automatically.

13.4.5.3 The “Quit Program” button is rarely used and will exit all ABCD programs and the temperature profile will stop. To restart, click arrow at the top left corner. You must then go to the DAQ Configuration tab and click the click the “Check Chamber Communication” button again to be connected with the chamber.

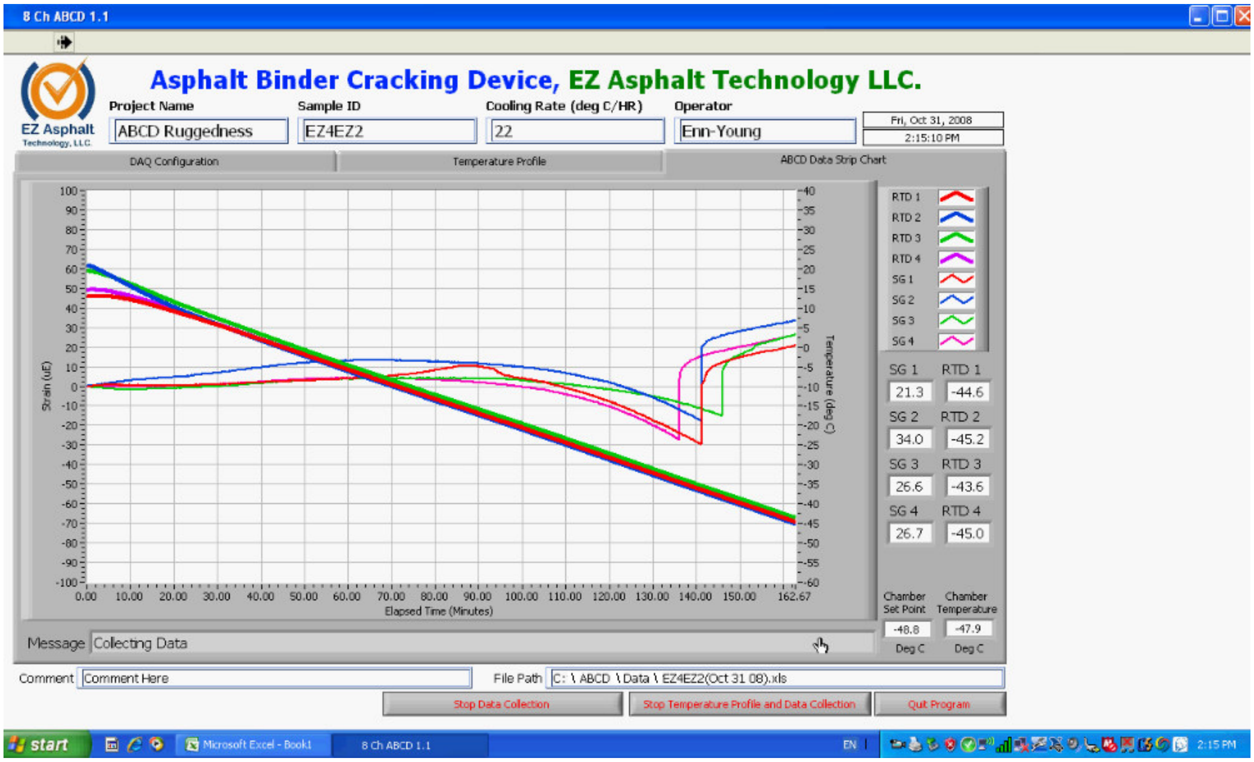


Project Name: ABCD Ruggedness
Sample ID: EZ2EZ3
Cooling Rate (deg C/HR): 22
Operator: KBE
Thu, Oct 30, 2008
5:15:31 PM

SG 1: 0.3
RTD 1: 14.4
SG 2: 0.0
RTD 2: 21.7
SG 3: 0.2
RTD 3: 20.3
SG 4: -0.1
RTD 4: 16.0
Chamber Set Point: 24.5 Deg C
Chamber Temperature: 24.9 Deg C

Message: Collecting Data
Comment: Comment Here
File Path: C: \ ABCD \ Data \ EZ2EZ3(Oct 30 08).xls

Step 13.4. ABCD Data Strip Chart tab at 0.17 minutes (10 sec) into a Test. The four ABCD ring strains all overlap at about 0 microstrains. The four ABCD ring temperatures are all slightly different at this early portion of the test, between 14.4 and 21.7°C. This particular test is conducted at a cooling rate of 22°C/hour. Your tests will generally follow the standard cooling rate of 20°C/hour.



Project Name: ABCD Ruggedness
Sample ID: EZ4EZ2
Cooling Rate (deg C/HR): 22
Operator: Enn-Young
Fri, Oct 31, 2008
2:15:10 PM

SG 1	RTD 1
21.3	-44.6

SG 2	RTD 2
34.0	-45.2

SG 3	RTD 3
26.6	-43.6

SG 4	RTD 4
26.7	-45.0

Chamber Set Point	Chamber Temperature
-48.8	-47.9
Deg C	Deg C

Message: Collecting Data
Comment: Comment Here
File Path: C: \ ABCD \ Data \ EZ4EZ2(Oct 31 08).xls

Step 13.4.4. ABCD Data Strip Chart tab at 162.67 minutes (2.71 hours) into a Test. The four binders all cracked between about 135 and 145 minutes into the test as indicated by the sudden strain jumps. The temperature of each of the four rings are indicated by the overlapping diagonal lines. The binders each cracked at around -33 to -36°C. The test should be continued until the entire temperature profile has completed so that the chamber temperature (and ring temperatures) rise to about 25°C. This helps to avoid condensation on the rings which occurs when the chamber door is opened while the chamber is still cold. Condensation on the rings reduces ring life.

14. Data Analysis

14.1 After the program has stopped running, it will automatically open an Excel spreadsheet containing all of the data collected.

14.2 Click the "ABC" icon located at the top of the window to run an analysis.

14.3 You will be prompted to enter a value for the strain jump.

14.3.1 A typical value is 5 (5 microstrains). However, a more appropriate value may be larger, such as 10 or 15. Discussion:

The Strain jump is a sudden strain increase due to occurrence of cracking. The cracking temperature is determined to be the temperature at which the strain increase between two consecutive data points exceeds the user input value of "Strain Jump to Define Cracking" (default = 5 microstrain). Please check the reasonableness of the cracking temperature since data noise sometimes can be misinterpreted as the cracking temperature by the program. If this happens, you may need to analyze the data with a different strain jump. Or you may enter the cracking temperature manually.

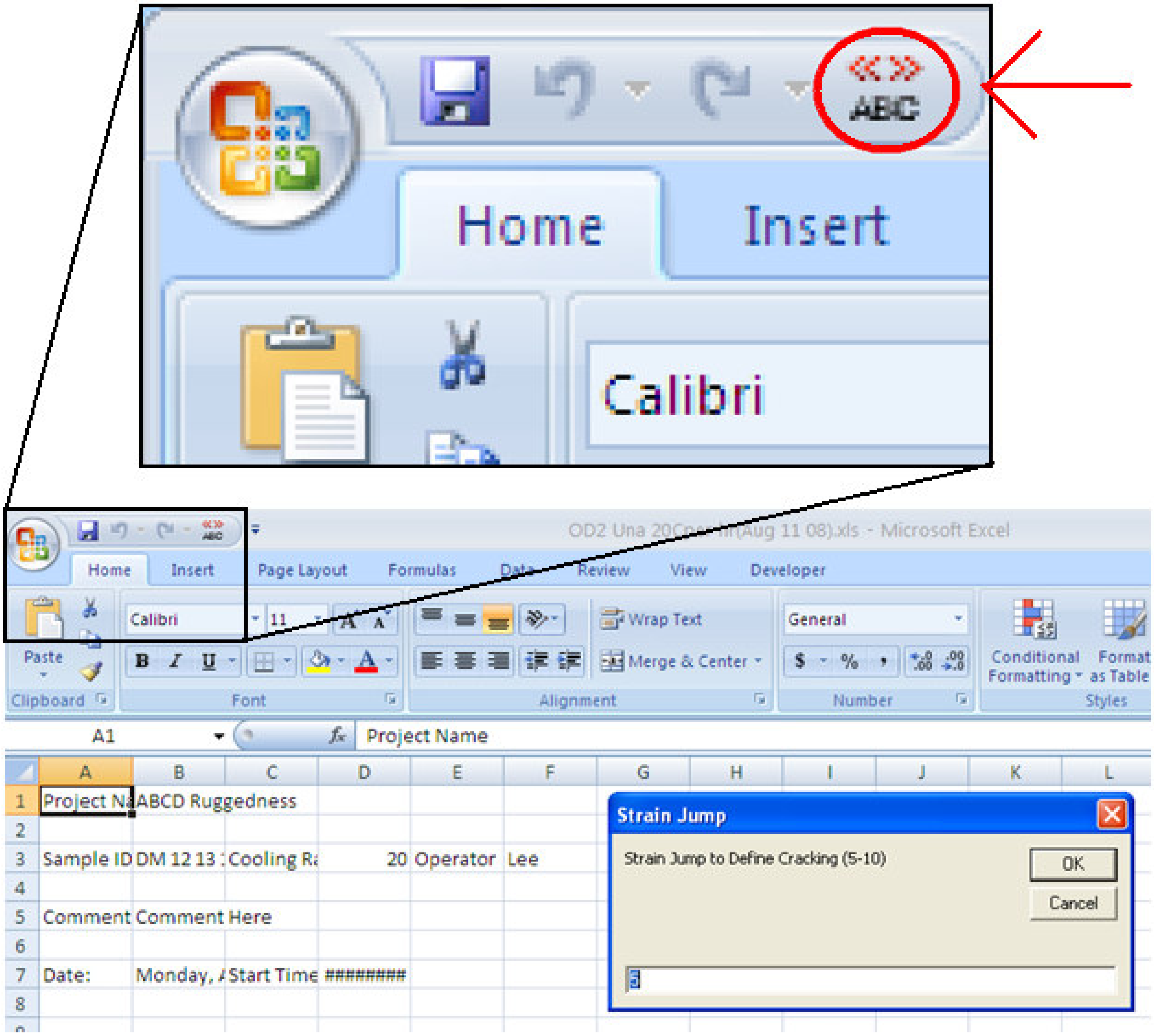
- 14.3.2 Click OK and the analysis macro will run.
- 14.3.3 After analysis, the cracking temperatures, strain jumps, and graph of strain versus temperature will display.

14.4 The spreadsheet will automatically be saved in the location that was assigned in the Temperature Profile pane. You do not need to save it again even though it may ask.

14.5 File locations.

- 14.5.1 Raw data files have .xls extensions and are located in the "C:\ABCD\Data" folder which is accessed by double-clicking the ABCD folder icon on the computer Desktop.
- 14.5.2 Analyzed files have .xls extensions and are located in the "C:\ABCD\Analyzed Tests" folder which is accessed by double-clicking the ABCD folder icon on the computer Desktop.
- 14.5.3 The computers run Excel 2007 but the files are Excel 2003 format.

14.6 Please see Appendix for further discussion of data analysis.



Project Name

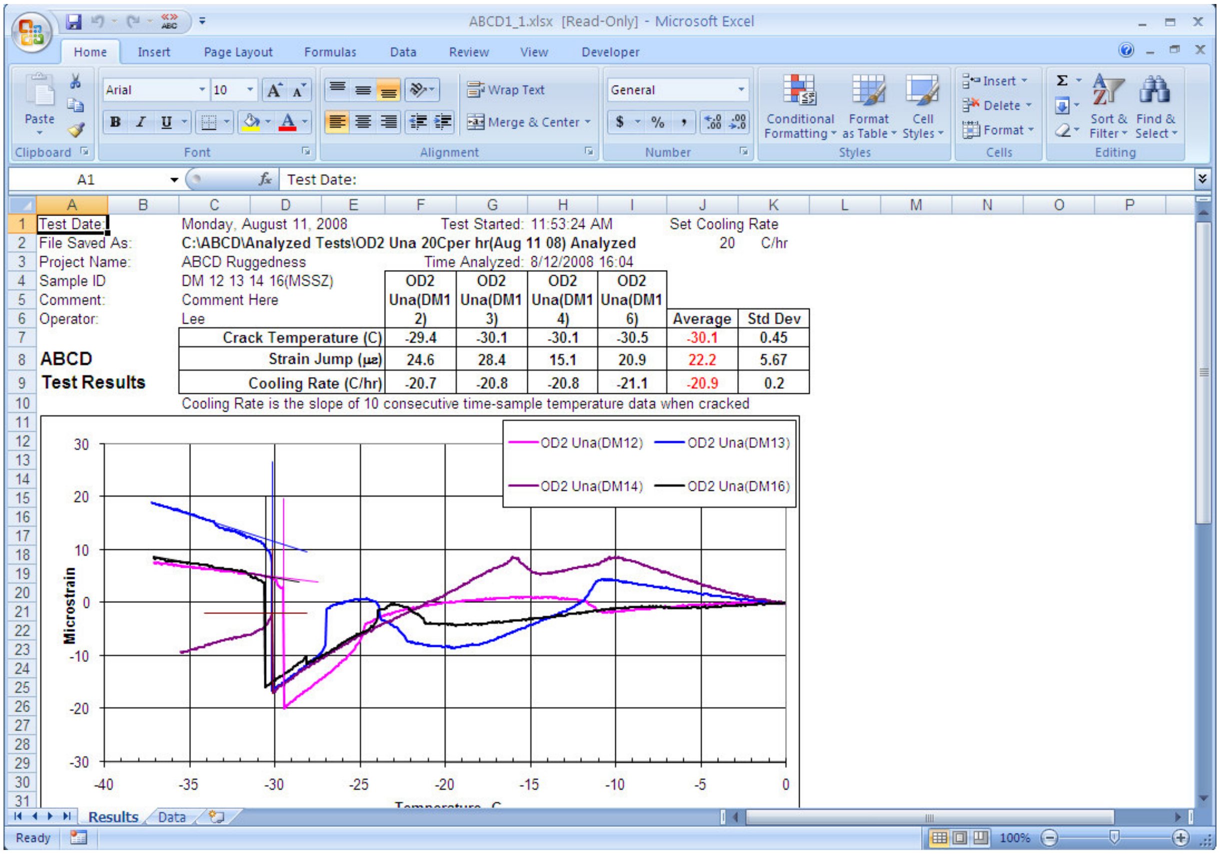
	A	B	C	D	E	F
1	Project Na	ABCD Ruggedness				
2						
3	Sample ID	DM 12 13 :	Cooling Ra	20	Operator	Lee
4						
5	Comment	Comment Here				
6						
7	Date:	Monday, /	Start Time	#########		
8						

Strain Jump

Strain Jump to Define Cracking (5-10)

5

Steps 14.2 and 14.3. Excel spreadsheet. Location of "ABC" analysis icon. Srain jump pop-up window.



Test Date: Monday, August 11, 2008 Test Started: 11:53:24 AM Set Cooling Rate
File Saved As: **C:\ABCD\Analyzed Tests\OD2 Una 20Cper hr(Aug 11 08) Analyzed** 20 C/hr
Project Name: ABCD Ruggedness Time Analyzed: 8/12/2008 16:04
Sample ID DM 12 13 14 16(MSSZ)
Comment: Comment Here
Operator: Lee

ABCD Test Results

	OD2 Una(DM12)	OD2 Una(DM13)	OD2 Una(DM14)	OD2 Una(DM16)	Average	Std Dev
Crack Temperature (C)	-29.4	-30.1	-30.1	-30.5	-30.1	0.45
Strain Jump (με)	24.6	28.4	15.1	20.9	22.2	5.67
Cooling Rate (C/hr)	-20.7	-20.8	-20.8	-21.1	-20.9	0.2

Cooling Rate is the slope of 10 consecutive time-sample temperature data when cracked

Step 14.3. Completed Data Analysis. Cracking temperatures, strain jumps, and graph of strain versus temperature. Note the temporary increase in strain for the blue curve at about -24°Cwhich is not the cracking temperature. The cracking temperatures are between -29.4 and -30.5°C as shown by the vertical profound strain jumps.

15. ABCD Assembly Removal, Disassembly, and Cleaning after Test Completion

15.1 Allow cooling chamber to warm to room temperature for at least 30 minutes following completion of test. This is completed automatically since the standard temperature profile has one hour of warming to 25°C following the cooling period.

15.2 Assembly Removal from Chamber

15.2.1 Open cooling chamber door.

15.2.2 Carefully remove wires from ABCD rings.

15.2.3 Remove ABCD assemblies from cooling chamber.

15.3 Disassembly

15.3.1 Using thumb in bottom hole of silicone mold, push ABCD ring out of binder.

15.3.2 Carefully remove asphalt binder from mold.

15.3.3 Observe binder for crack at protrusion and quality of specimen.

15.4 Clean Molds

15.4.1 Wash silicone molds in soapy water with paper towel to remove asphalt stains.

15.4.2 Rinse molds in clean water.
15.4.3 Rinse again in another clean water bath.
15.4.4 Dry molds with towel or rag.

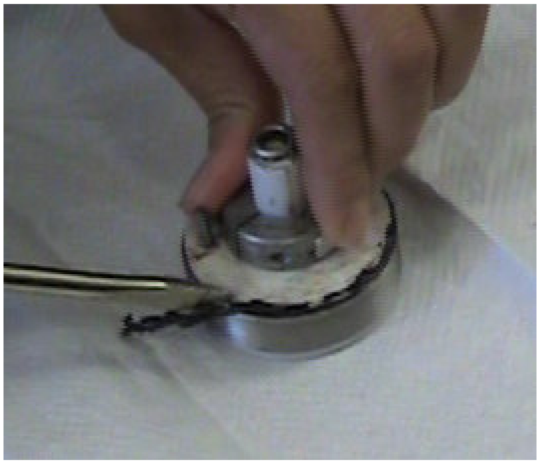
Step 15.4.1. Cleaning mold in soapy water with paper towel.

15.5 Clean ABCD Rings and Covers

15.5.1 Wipe all outside portions of ABCD ring and plastic covers with paper towel.

15.5.2 Use screwdriver to carefully remove binder from ABCD ring without notching the ring. Do not clean rings with water. Can use kerosene to remove binder stains from ring and covers. Kerosene may be necessary after about five tests.

Step 15.5.1. Cleaning ring with paper towel.



Step 15.5.2. Screwdriver to carefully remove binder from ABCD ring.

Appendix
Interpretation of ABCD Data

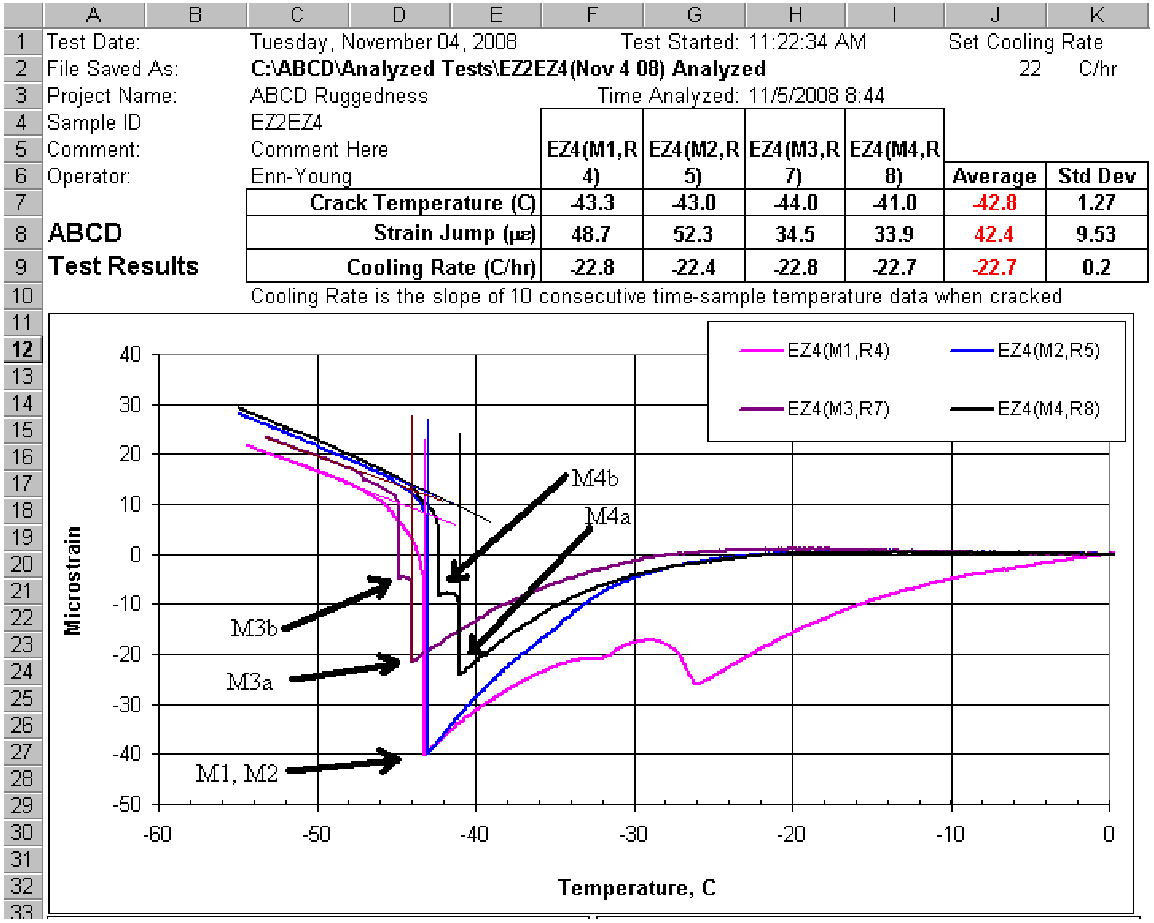
Discussion of Figure A1

Figure A1 is the analyzed graph of ABCD data for the Nov. 4, 2008, ruggedness test of the EZ4 binder (PG64-34M SBS RTFO/PAV aged) at a cooling rate of 22°C/hr. What is the true cracking temperature of each specimen? Specimens M1 and M2 each have one large strain jump of 48.7 and 52.3 microstrains, so their cracking temperatures are easily identified by our Microsoft Excel analysis macro as -43.3°C and -43.0°C, respectively. However, specimens M3 and M4 each have two strain jumps of moderate magnitudes. Did specimen M3 crack at the higher temperature strain jump (M3a) or at the lower temperature strain jump (M3b)? The strain and temperature gages are located inside the ABCD ring and the ring is aligned with the pink mold such that the strain and temperature sensors line up with the protrusion. We believe the warmer jump (M3a) is caused by crack formation above the mold protrusion. Due to heat transfer, the chamber temperature may propagate downward through the binder, so the crack may be starting on the top of the protrusion and working its way downward resulting in a second strain jump at M3b at a lower temperature than M3a's crack.

Did specimen M4 crack at the higher temperature jump (M4a) or at the lower temperature jump (M4b)? The discussion is the same as for M3a versus M3b in the previous paragraph.

What is happening to specimen M1 at about -26°C to -30°C? This is an interaction between plastic cover and ring. The plastic cover has a higher thermal expansion coefficient than the Invar ring. The cover is connected to the ring through three small diameter (1/32" diameter x 5/16" long) pins. The contraction of the plastic cover pulls on the pins which likewise pull on the Invar ring causing the decrease in strain to -26°C. The pins then slip causing the ring to relax and the strain to increase. This phenomena is okay and does not affect the binder cracking temperature determination; however, the problem has been resolved by making the ring holes larger in more recent rings. The other three specimens did not exhibit this behavior because the pins were freer to slide in these rings.

Figure A1. Analysis of binder EZ4 during ruggedness testing at 22°C/hr cooling rate.



Test Date: Tuesday, November 04, 2008 Test Started: 11:22:34 AM Set Cooling Rate

File Saved As: **C:\ABCD\Analyzed Tests\EZ2EZ4(Nov 4 08) Analyzed** 22 C/hr

Project Name: ABCD Ruggedness Time Analyzed: 11/5/2008 8:44

Sample ID EZ2EZ4

Comment: Comment Here

Operator: Enn-Young

ABCD
Test Results

	EZ4(M1,R4)	**EZ4(M2,R5)**	**EZ4(M3,R7)**	**EZ4(M4,R8)**	**Average**	**Std Dev**
Crack Temperature (C)	**-43.3**	**-43.0**	**-44.0**	**-41.0**	**-42.8**	**1.27**
Strain Jump (µε)	**48.7**	**52.3**	**34.5**	**33.9**	**42.4**	**9.53**
Cooling Rate (C/hr)	**-22.8**	**-22.4**	**-22.8**	**-22.7**	**-22.7**	**0.2**

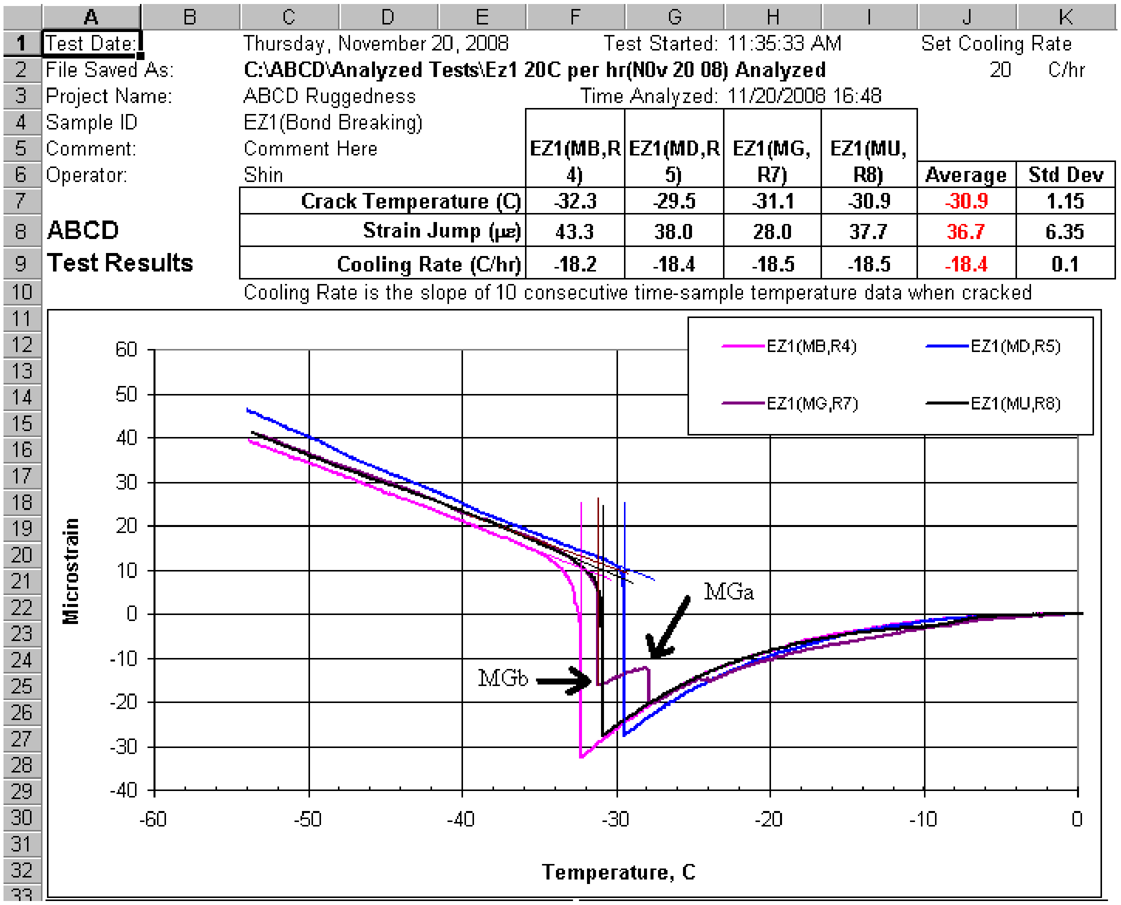
Cooling Rate is the slope of 10 consecutive time-sample temperature data when cracked

Discussion of Figure A2

Figure A2 is the analyzed graph of ABCD data for the Nov. 20, 2008, ruggedness test of the EZ1 binder (PG64-16 AAM-1 RTFO/PAV aged) at a cooling rate of 20°C/hr. What is the true cracking temperature of each specimen? Specimens MB, MD, and MU each have one large strain jump of 43.3, 38.0, and 37.7 microstrains, so their cracking temperatures are easily identifiable by the analysis macro as -32.3°C, -29.5°C, and -30.9°C, respectively. However, specimen MG has two strain jumps of moderate magnitudes. Did specimen MG crack at the higher temperature jump (MGa) or at the lower temperature jump (MGb)? Unlike specimens M3 and M4 in Figure A1 where the two jumps were caused by vertical temperature propagation at the protrusion, here the mechanism is circumferential friction release between binder and ring. After the first strain release (MGa), the strain continues to drop. This is a sign that the binder was grabbing the ring by friction during cooling. Eventually (at about -28°C), the binder stopped grabbing the ring and slipped thus releasing strain. We believe this was not due to cracking. The binder then continued to cool and contract on the ring. Finally, the binder cracked at -31.1°C as indicated by the strain jump MGb.

If there are multiple strain jumps, in general the lower temperature jump indicates the binder cracking temperature. Higher temperature strain jumps are likely occurring due to friction release of the pins connecting the cover to the ring or friction release between the binder and ring, rather than binder cracking. However, the exception to this is Figure A1 where there are two strain jumps but the higher temperature jump is a crack above the protrusion that has not yet propagated below the protrusion.

Figure A2. Analysis of binder EZ1 during ruggedness testing at 20°C/hr cooling rate.



Test Date: Thursday, November 20, 2008 Test Started: 11:35:33 AM Set Cooling Rate

File Saved As: **C:\ABCD\Analyzed Tests\Ez1 20C per hr(N0v 20 08) Analyzed** 20 C/hr

Project Name: ABCD Ruggedness Time Analyzed: 11/20/2008 16:48

Sample ID EZ1(Bond Breaking)

Comment: Comment Here

Operator: Shin

ABCD

Test Results

	EZ1(MB,R4)	EZ1(MD,R5)	EZ1(MG, R7)	EZ1(MU, R8)	Average	Std Dev
Crack Temperature (C)	-32.3	-29.5	-31.1	-30.9	-30.9	1.15
Strain Jump (με)	43.3	38.0	28.0	37.7	36.7	6.35
Cooling Rate (C/hr)	-18.2	-18.4	-18.5	-18.5	-18.4	0.1

Cooling Rate is the slope of 10 consecutive time-sample temperature data when cracked

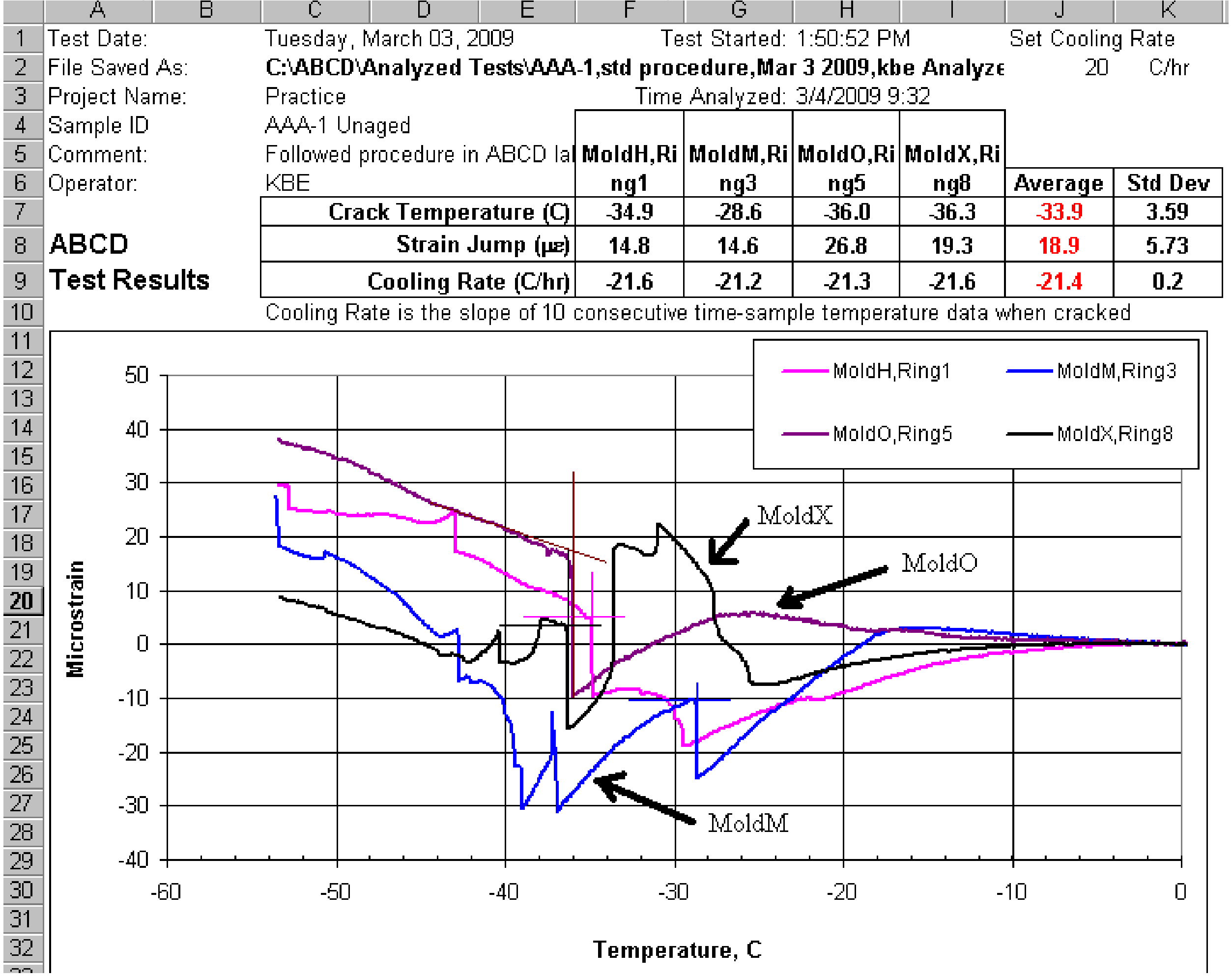
Discussion of Figure A3

Figure A3 is the analyzed graph of ABCD data for a March 3, 2009, test of the AAA-1 binder at a cooling rate of 20°C/hr. What is the true cracking temperature of each specimen? Occasionally test results will look unruly like this with multiple strain jumps. The strain variation in specimen MoldX from -25°C to -34°C is due to the plastic cover/ring interaction as discussed above for Figure A2 specimen MG. A similar phenomenon is occurring for MoldO where the strain increases around -25°C. The plastic cover is contracting as the temperature drops. Due to the location of the pins connecting the plastic cover to the ring and the fact that the friction connecting each pin to the ring may be slightly different, there is expansion of the ring rather than contraction at the sensor location in the -25°C range. The ring may be contracting elsewhere along the circumference due to cover contraction, but the ring is expanding in the vicinity of the strain sensor.

The sudden jumps in MoldM strain are likely due to lubrication deficiency in the ring and mold preparation. If the rings are ever cleaned with acetone (possibly after 20 runs) to remove stains, it is important to put a very light coat of silicone grease on the ring (and wipe off thoroughly leaving only a very thin film. We use Dow Corning High Vacuum Grease silicone lubricant) . Then brush the ring with glycerine/talc lubricant as described in the laboratory procedure above. Lack of lubrication causes the binder to adhere to the ring, then release from the ring, then re-adhere, until the binder finally cracks as indicated by the lowest temperature strain jump.

Though some of the cracking temperatures may be reliable for this data, it would be best to re-run the binder. A newer ring design has generally overcome this problem.

Figure A3. Analysis of binder AAA-1 during test at 20°C/hr cooling rate.



Test Date: Tuesday, March 03, 2009 Test Started: 1:50:52 PM Set Cooling Rate
File Saved As: **C:\ABCD\Analyzed Tests\AAA-1,std procedure,Mar 3 2009,kbe Analyze** 20 C/hr
Project Name: Practice Time Analyzed: 3/4/2009 9:32
Sample ID AAA-1 Unaged
Comment: Followed procedure in ABCD lal
Operator: KBE

ABCD
Test Results

	MoldH,Ring1	**MoldM,Ring3**	**MoldO,Ring5**	**MoldX,Ring8**	**Average**	**Std Dev**
Crack Temperature (C)	**-34.9**	**-28.6**	**-36.0**	**-36.3**	**-33.9**	**3.59**
Strain Jump (µε)	**14.8**	**14.6**	**26.8**	**19.3**	**18.9**	**5.73**
Cooling Rate (C/hr)	**-21.6**	**-21.2**	**-21.3**	**-21.6**	**-21.4**	**0.2**

Cooling Rate is the slope of 10 consecutive time-sample temperature data when cracked

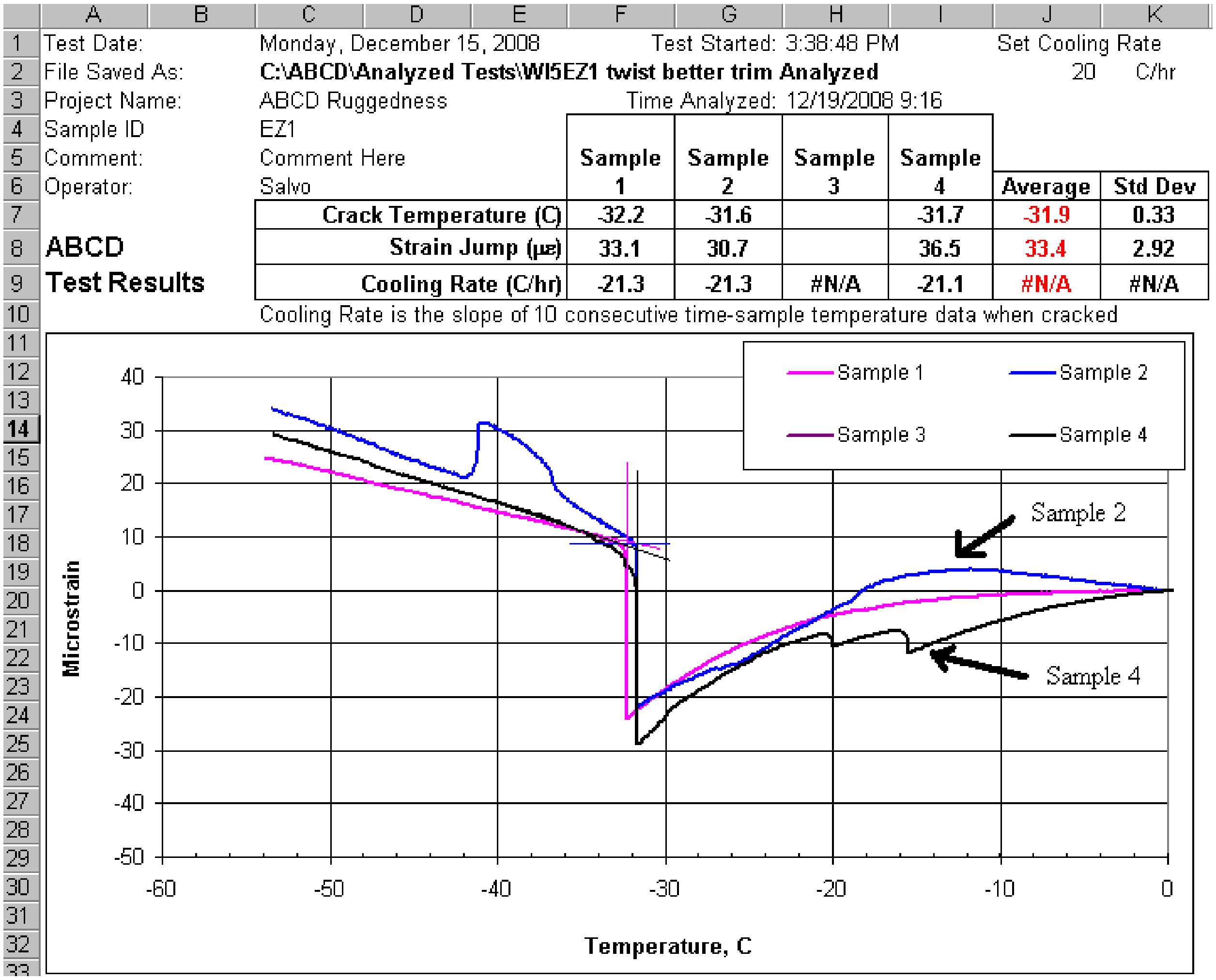
Discussion of Figure A4

The cracking temperatures are well-defined in this test. Specimen Sample 3 was not run so no data is present for it. Three samples are sufficient for reliable cracking temperature determination.

Sample 2 shows an increase in strain up to about -12^{o}C due to the thermal contraction of the plastic cover being transmitted to the ring and strain sensor through three small pins. The strain increases to about -12^{o}C for the same reason as in Figure A3 specimen MoldO.

Sample 4 shows similar behavior at the strain increases at -16^{o}C and -20^{o}C. Though these strain increases are more abrupt than the gradual Sample 2 increase, we believe it is the same phenomenon and not releasing of friction between ring and binder. Releasing of friction between ring and binder causes a very vertical strain jump.

Figure A4. Analysis by Univ. of Wisconsin of binder EZ1 during test at 20^{o}C/hr cooling rate.



Test Date: Monday, December 15, 2008 Test Started: 3:38:48 PM Set Cooling Rate

File Saved As: **C:\ABCD\Analyzed Tests\WI5EZ1 twist better trim Analyzed** 20 C/hr

Project Name: ABCD Ruggedness Time Analyzed: 12/19/2008 9:16

Sample ID EZ1

Comment: Comment Here

Operator: Salvo

ABCD
Test Results

	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Average**	**Std Dev**
Crack Temperature (C)	**-32.2**	**-31.6**		**-31.7**	**-31.9**	**0.33**
Strain Jump (με)	**33.1**	**30.7**		**36.5**	**33.4**	**2.92**
Cooling Rate (C/hr)	**-21.3**	**-21.3**	**#N/A**	**-21.1**	**#N/A**	**#N/A**

Cooling Rate is the slope of 10 consecutive time-sample temperature data when cracked