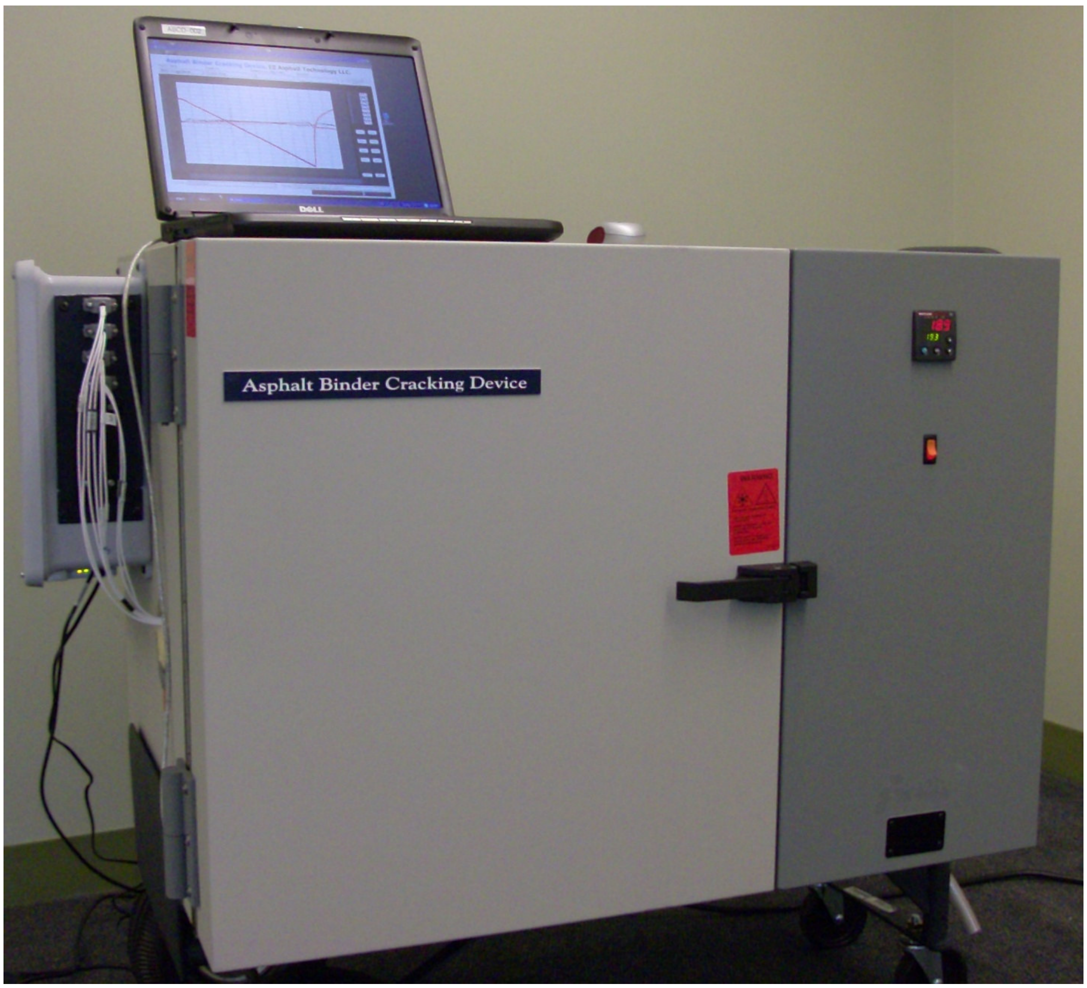
INNOVATIONS IN ASPHALT TESTING

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.

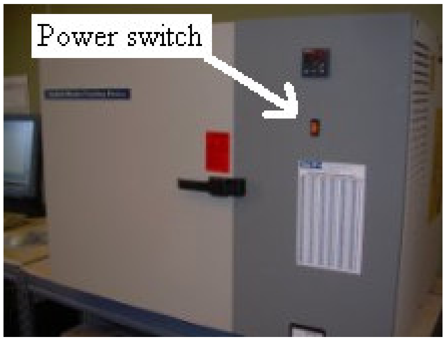
Please see our promotional video at http://www.EZasphaltTechnology.com and procedure video at http://www.EZasphaltTechnology.com/products/abcd/training.php (note procedure video has not been updated as of 3/24/09 to show room temperature cooling in Section 9 of procedure or ring rotation in Section 11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

Detailed procedure

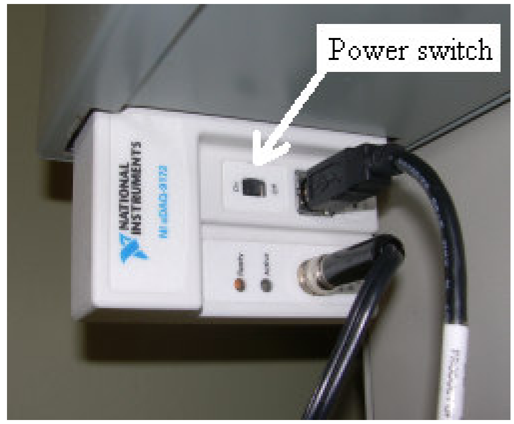
1. Safety Precautions
    - 1.1 Latex gloves helpful to keep binder off hands.
    - 1.2 Insulated gloves necessary when holding heated asphalt container and pouring.
    - 1.3 Safety glasses recommended when working with hot binder.

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.

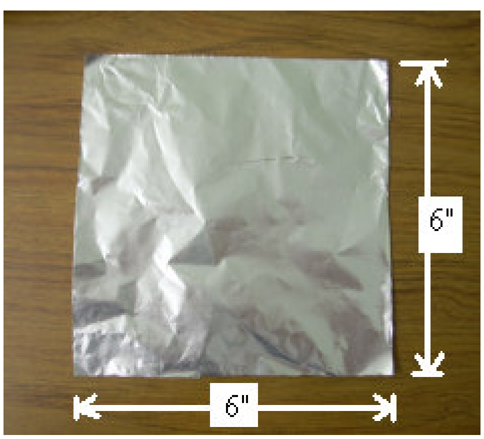


Step 2.1. Cooling chamber. Power switch up in "On" position.

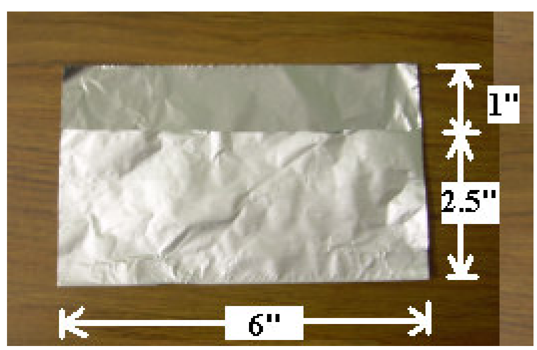


Step 2.2. Data collection hardware. Power switch pushed left in "On" position.

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^{o} (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.

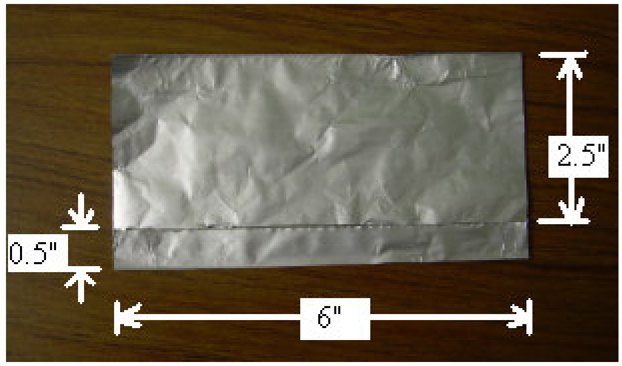


Step 3.1. Aluminum foil.

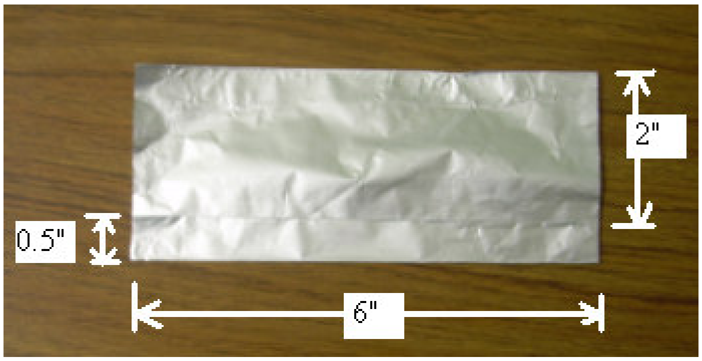


Step 3.2. First crease.

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.

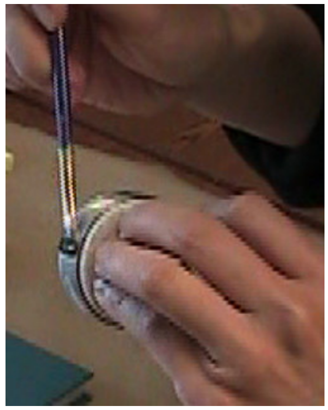

Step 4.3. Mold foil onto container for good seal.


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.

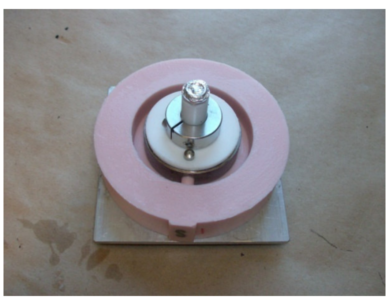
6. Lubrication
    - 6.1 Lubricant should be glycerin/talc mixture in 1:1 mass ratio.
    - 6.2 Lubricate four molds (or eight if you have an 8-ring system) using a brush.
        - 6.2.1 Apply lubricant to inside portions of mold where the ring and binder will contact the mold.
        - 6.2.2 Lubricate 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.



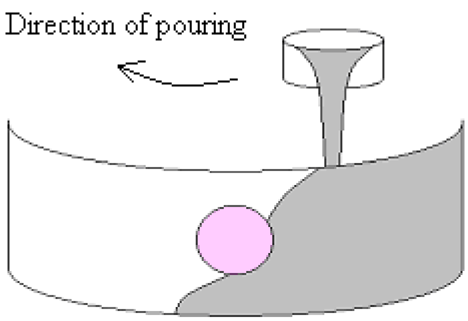
Step 6.3.2. Lubricate ring.

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

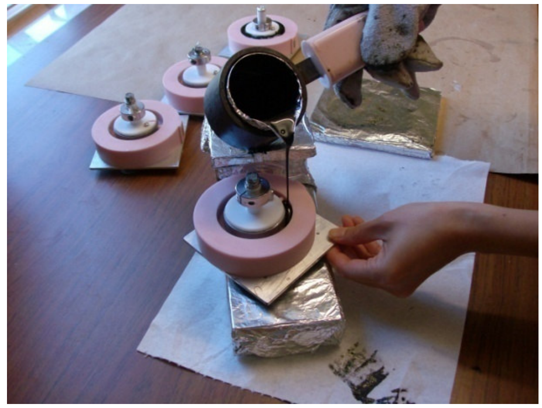


Step 7.3 Completed assembly.

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.



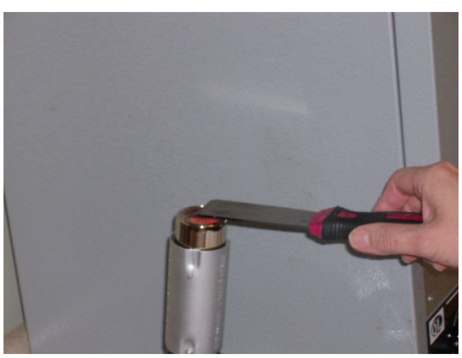
Step 8.2. Pouring.



Step 8.2. Pouring.

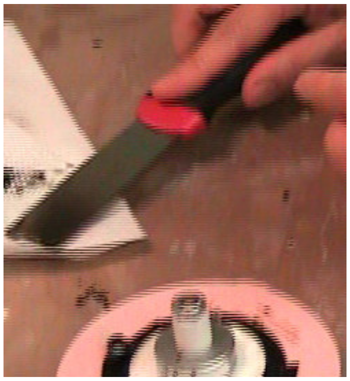
9. Room Temperature Cooling
    9.1 After all molds have been filled, let them all sit at room temperature for at least 1 hour.

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^{o} and 45^{o} 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.

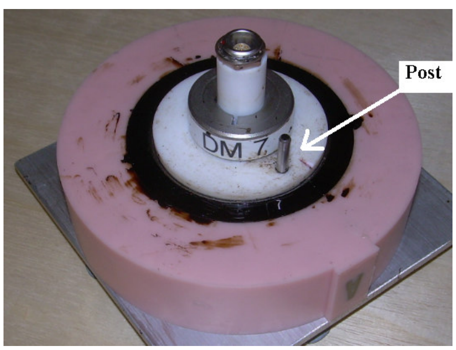


Step 10.3. Clean spatula by wiping on towel.

Step 10.3. Re-heat spatula

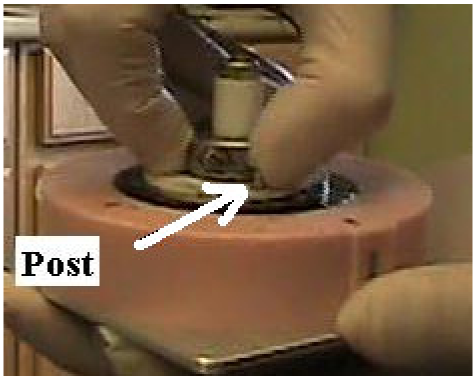
Step 10.3. Trim binder.

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.

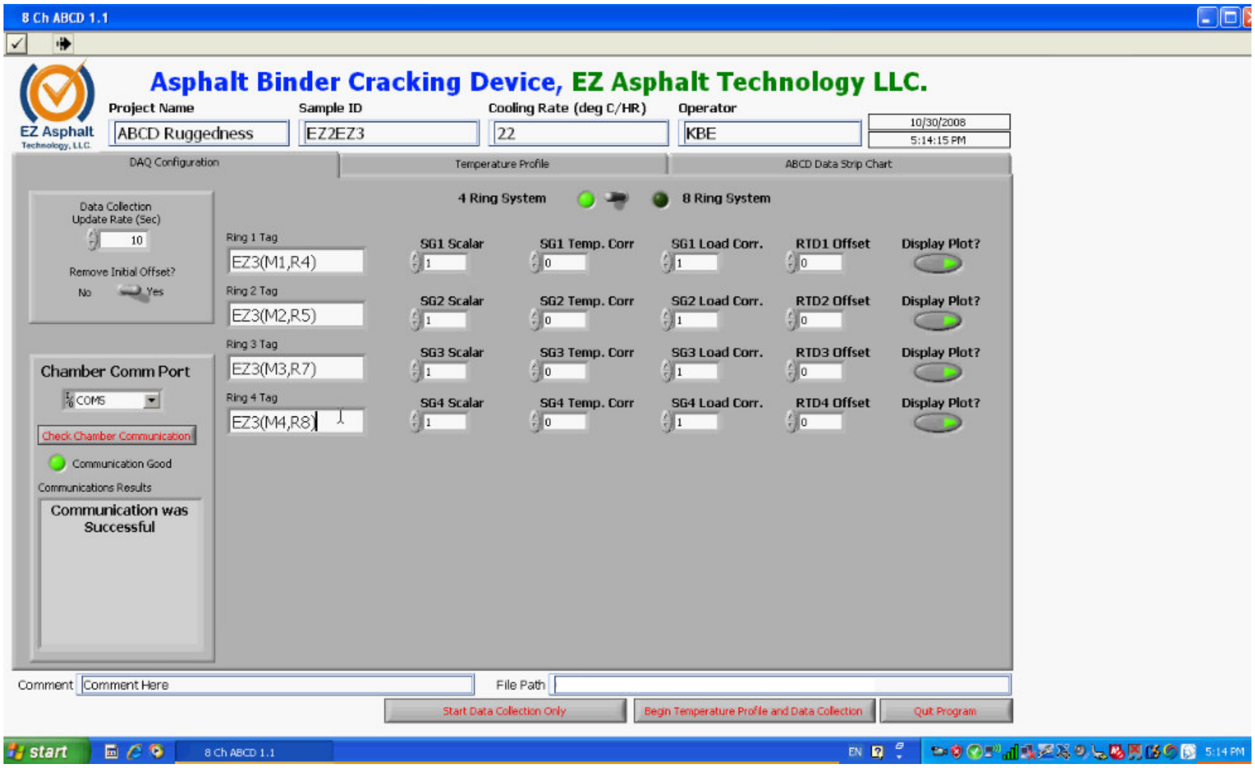
13.2.7 Check that "SG1 Temp. Corr", "SG2 Temp. Corr", etc. are set at 0.

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.



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 cannnot 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^{o}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^{o}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^{o}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^{o}C after 3.5 hours.

13.3.5.8 Set Point 4 should be entered as 25 (i.e. 25^{o}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^{o}C).

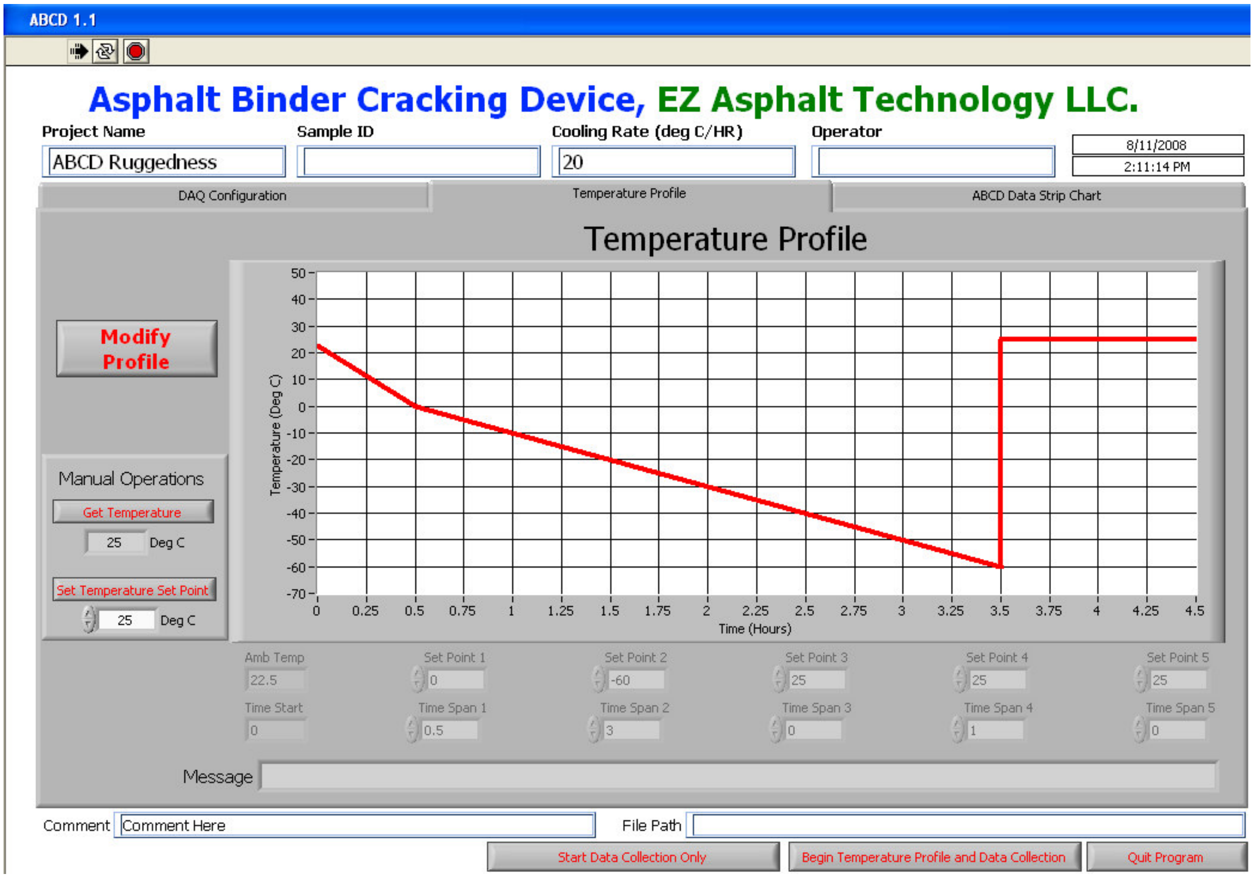
13.3.5.11 Time Span 5 should be entered as 0 (i.e. 0 hours). The chamber is warmed to 25^{o}C after the test in order to reduce condensation on the rings when the chamber door is opened..

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.

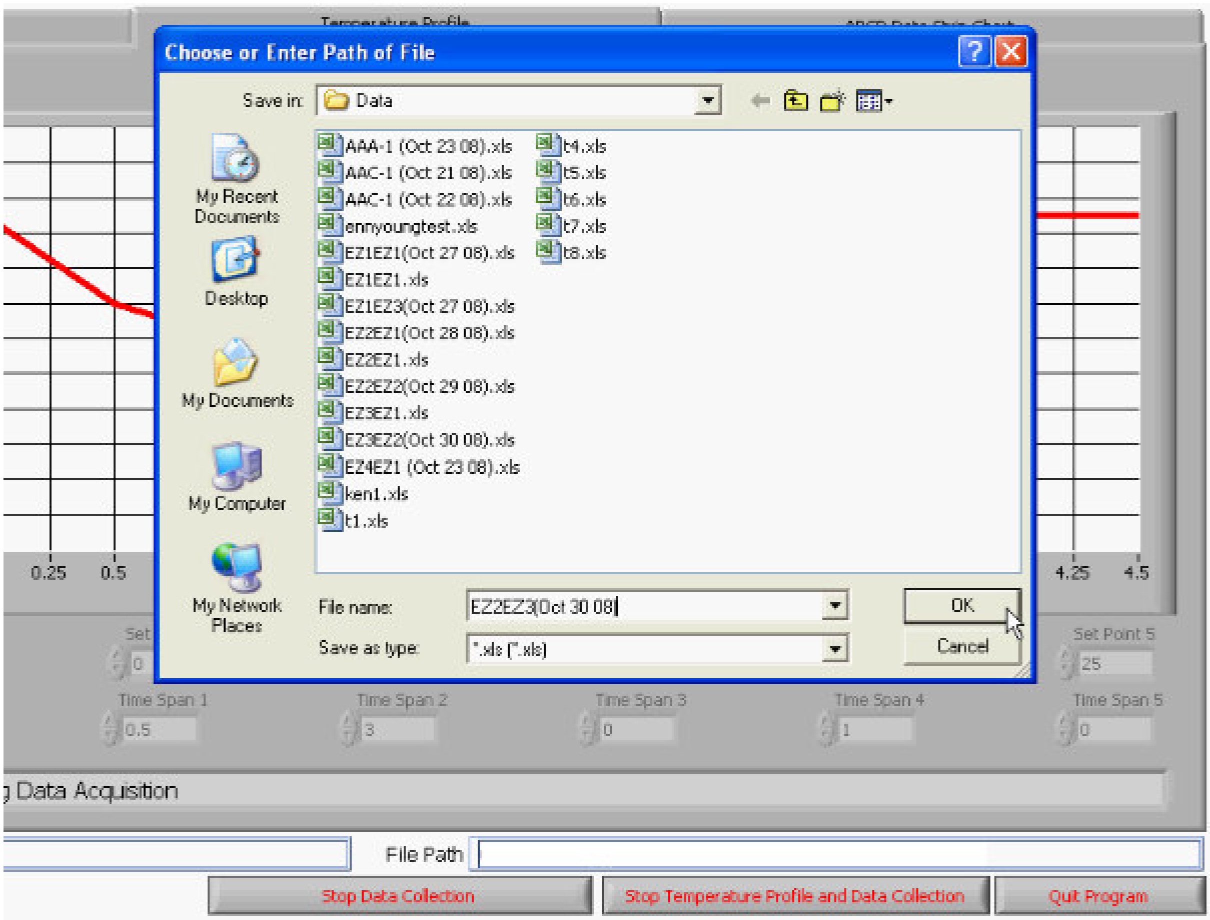
13.3.7 Click the “Begin Temperature Profile and Data Collection” button located in the bottom right hand corner.

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.



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



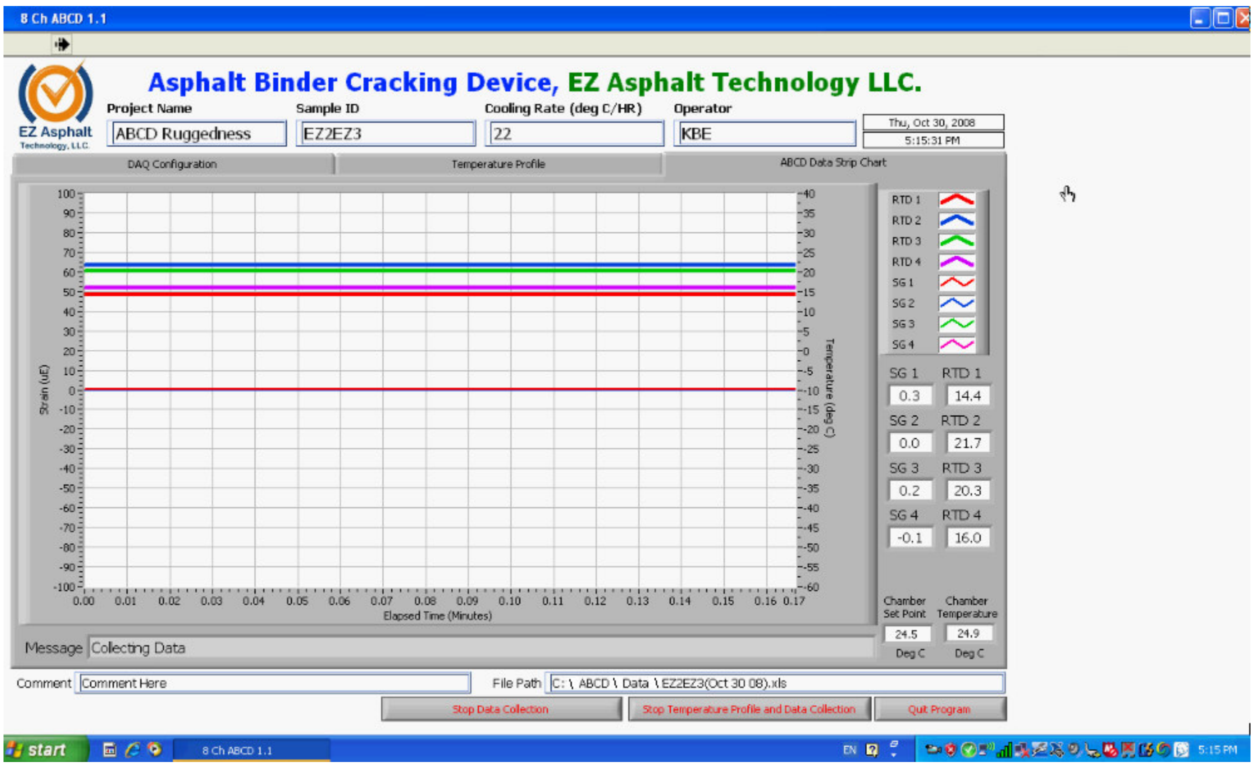
Step 13.3.7.1. Type file name. The ".xls" extension is automatically put on end of file name.

13.4 Click on the "ABCD Data Strip Chart" tab to monitor data collection.

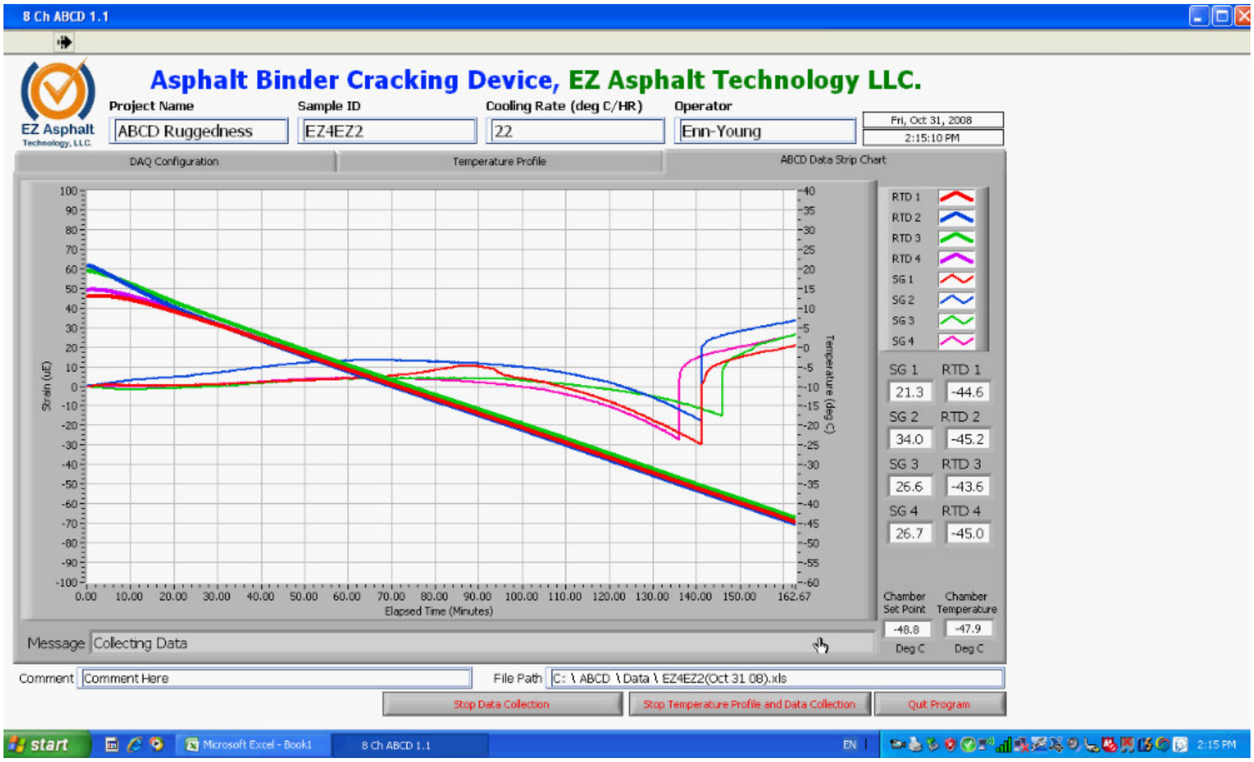
- 13.4.1 The graphs are updated at the time interval entered in Step 13.2.3 above. The maximum value on the time scale on the x-axis automatically increases as more data is collected.
- 13.4.2 "SG1, RTD1" and so on are Strain Gage and RTD (Resistance Temperature Device) temperature values for each ring.
- 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.



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.



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.

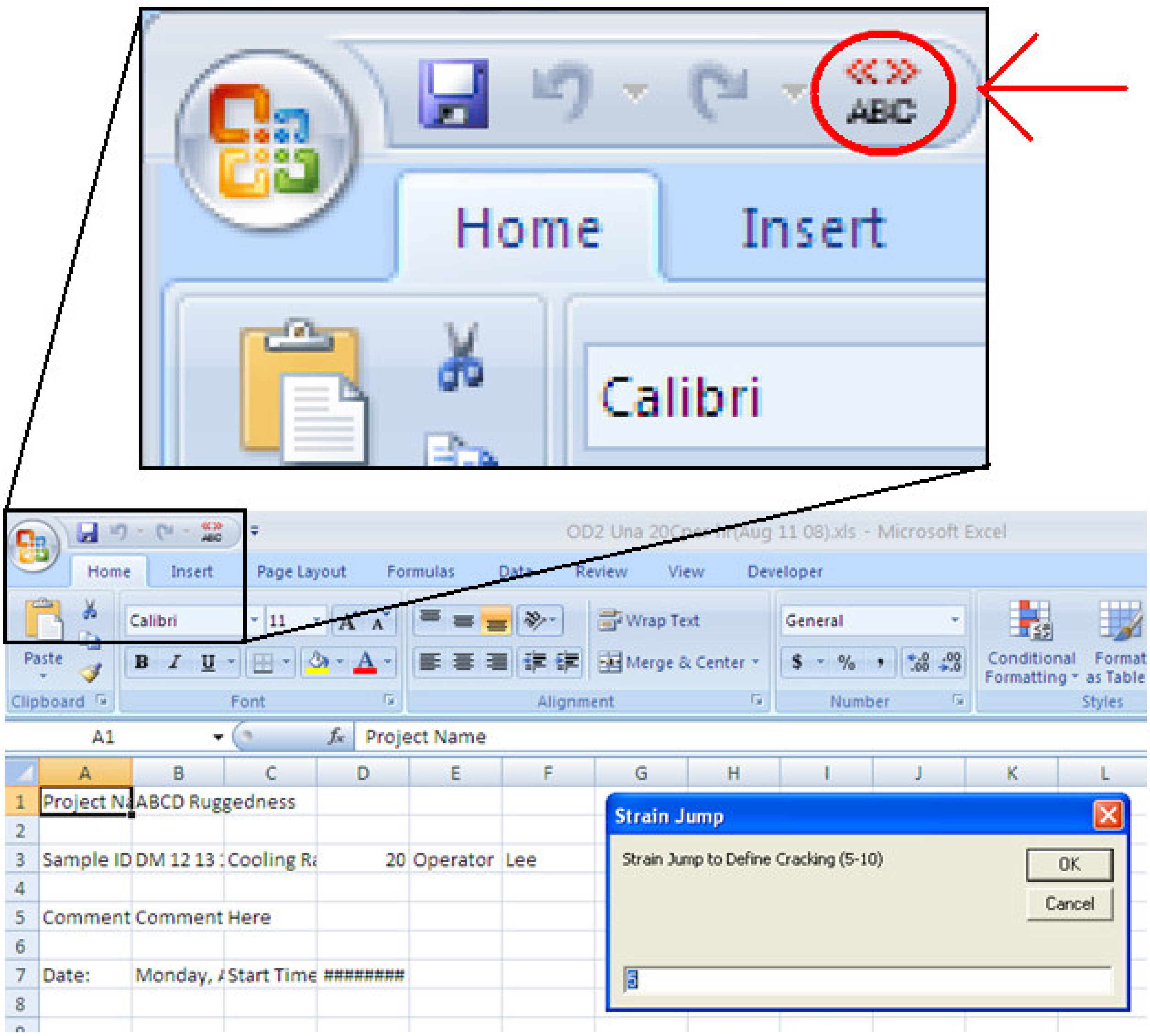
14.5 File locations.

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.

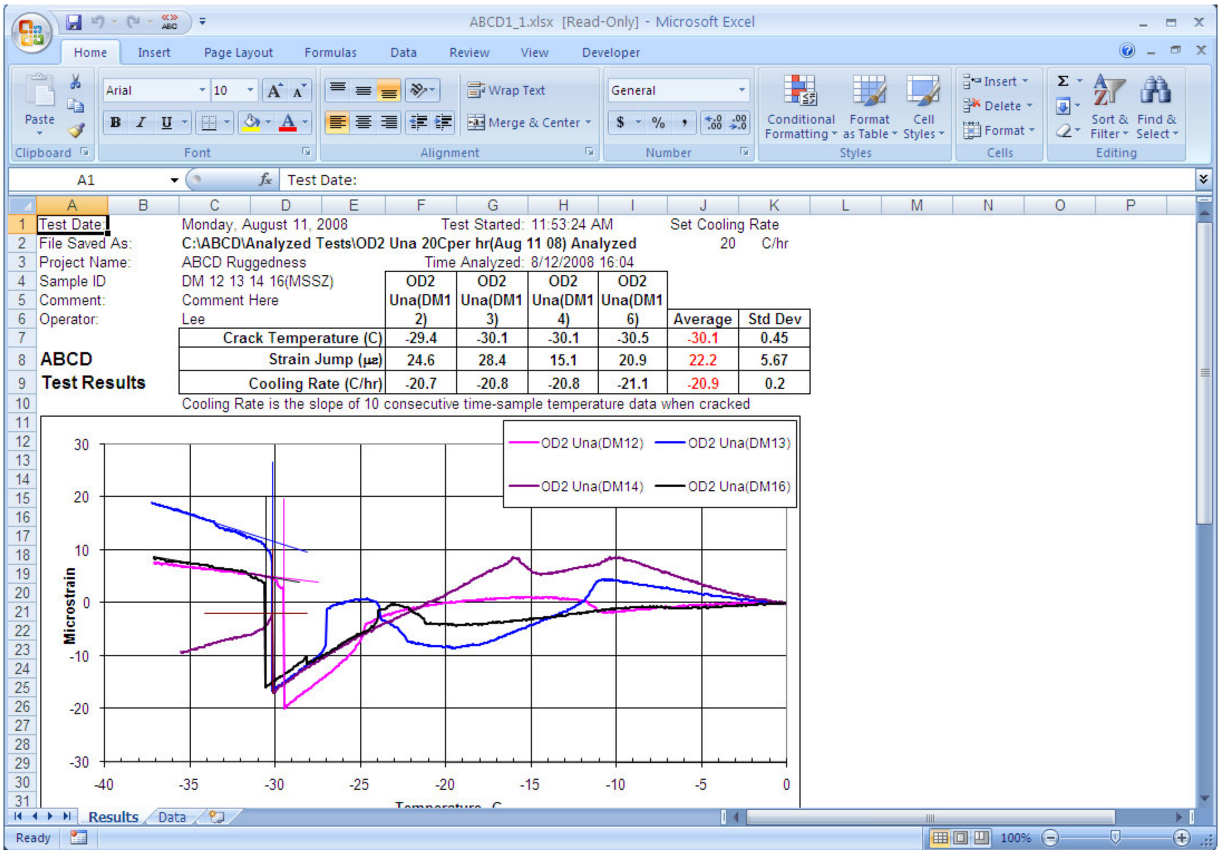
14.5.2 Analyzed files have .xls extensions and are located in the "C:\ABCD\Analyzed Tests" folder which is accessed by double-clicking the ABCD folder icon on the computer Desktop.

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.



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



	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

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

<u>Discussion of Figure A1</u>

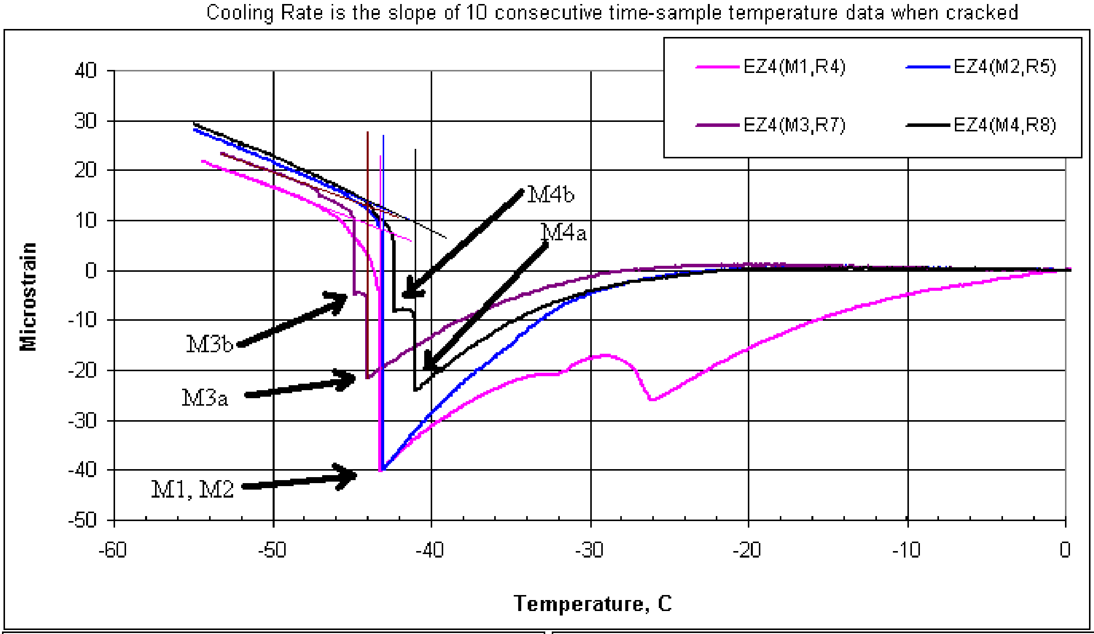
Figure A1 is the analyzed graph of ABCD data for the Nov. 4, 2008, ruggedness test of the EZ4 binder (PG64-34M SBS RTFO/PAV aged) at a cooling rate of 22^{o}C/hr. What is the true cracking temperature of each specimen? Specimens M1 and M2 each have one large strain jump of 48.7 and 52.3 microstrains, so their cracking temperatures are easily identified by our Microsoft Excel analysis macro as -43.3^{o}C and -43.0^{o}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^{o}C to -30^{o}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^{o}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.

	A	B	C	D	E	F	G	H	I	J	K
1	Test Date:		Tuesday, November 04, 2008			Test Started: 11:22:34 AM				Set Cooling Rate	
2	File Saved As:		C:\ABCD\Analyzed Tests\EZ2EZ4(Nov 4 08) Analyzed							22	C/hr
3	Project Name:		ABCD Ruggedness			Time Analyzed: 11/5/2008 8:44					
4	Sample ID		EZ2EZ4								
5	Comment:		Comment Here			EZ4(M1,R4)	EZ4(M2,R5)	EZ4(M3,R7)	EZ4(M4,R8)		
6	Operator:		Enn-Young							Average	Std Dev
7			Crack Temperature (C)			-43.3	-43.0	-44.0	-41.0	-42.8	1.27
8	**ABCD**		Strain Jump (με)			48.7	52.3	34.5	33.9	42.4	9.53
9	**Test Results**		Cooling Rate (C/hr)			-22.8	-22.4	-22.8	-22.7	-22.7	0.2
10			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^{o}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^{o}C, -29.5^{o}C, and -30.9^{o}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^{o}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^{o}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

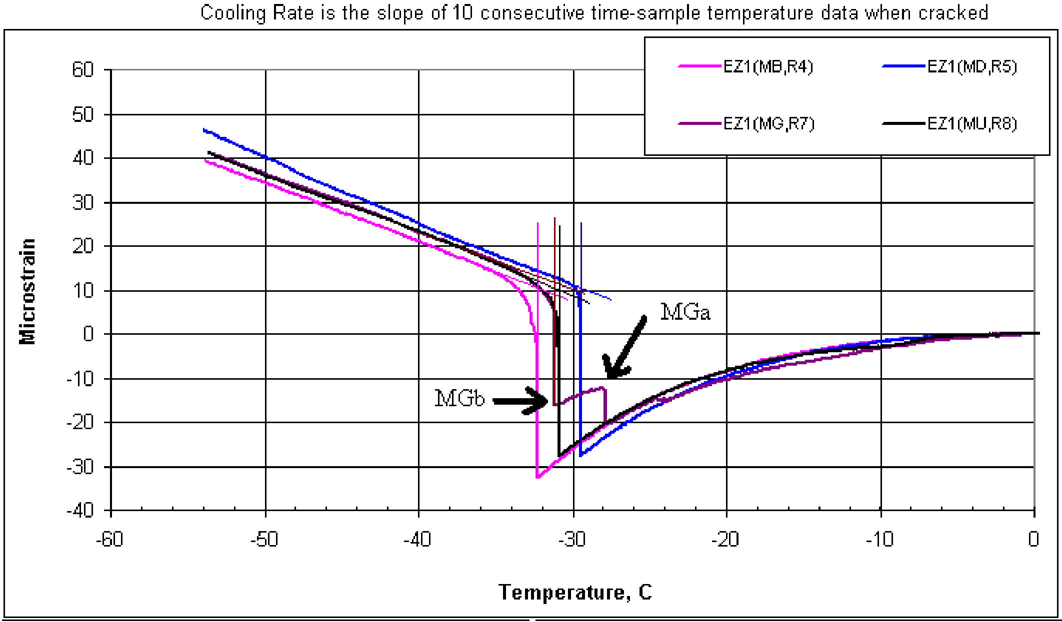
Sample ID EZ1(Bond Breaking)

Comment: Comment Here

Operator: Shin

		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**
ABCD	**Strain Jump (με)**	**43.3**	**38.0**	**28.0**	**37.7**	**36.7**	**6.35**
Test Results	**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

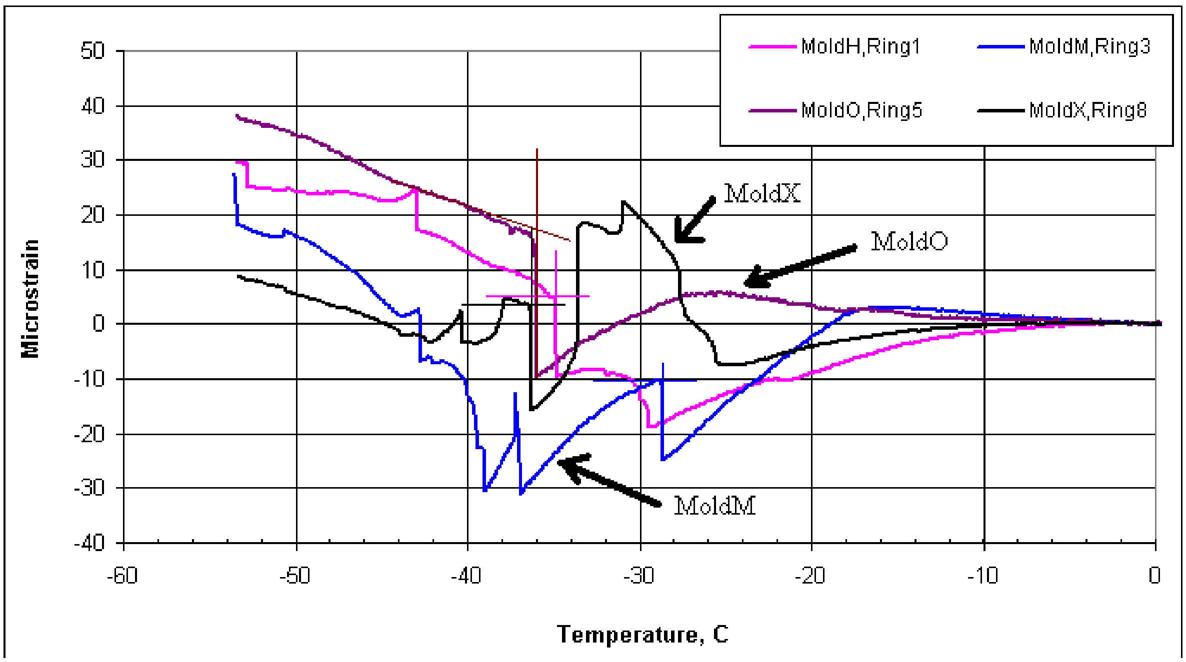
Figure A3 is the analyzed graph of ABCD data for a March 3, 2009, test of the AAA-1 binder at a cooling rate of 20°C/hr. What is the true cracking temperature of each specimen? Occasionally test results will look unruly like this with multiple strain jumps. The strain variation in specimen MoldX from -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^{o}C/hr cooling rate.

	A	C	F	G	H	I	J	K
1	Test Date:	Tuesday, March 03, 2009	Test Started: 1:50:52 PM				Set Cooling Rate	
2	File Saved As:	C:\ABCD\Analyzed Tests\AAA-1,std procedure,Mar 3 2009,kbe Analyze					20	C/hr
3	Project Name:	Practice	Time Analyzed: 3/4/2009 9:32					
4	Sample ID	AAA-1 Unaged						
5	Comment:	Followed procedure in ABCD lal	**MoldH,Ring1**	**MoldM,Ring3**	**MoldO,Ring5**	**MoldX,Ring8**		
6	Operator:	KBE					**Average**	**Std Dev**
7		**Crack Temperature (C)**	**-34.9**	**-28.6**	**-36.0**	**-36.3**	**-33.9**	**3.59**
8	**ABCD**	**Strain Jump (με)**	**14.8**	**14.6**	**26.8**	**19.3**	**18.9**	**5.73**
9	**Test Results**	**Cooling Rate (C/hr)**	**-21.6**	**-21.2**	**-21.3**	**-21.6**	**-21.4**	**0.2**
10		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°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°C for the same reason as in Figure A3 specimen MoldO.

Sample 4 shows similar behavior at the strain increases at -16°C and -20°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°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