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Highway IDEA Program

Development of an Asphalt Binder Cracking Device

Final Report for Highway IDEA Project 99

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DEVELOPMENT OF AN ASPHALT BINDER CRACKING DEVICE

IDEA Program Draft Final Report

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EXECUTIVE SUMMARY

The low temperature thermal cracking of asphalt pavements is one of the main causes for annually repeating expensive highway repairs. While the current Association of American State Highway and Transportation Officials (AASHTO) M 320 Table 1 binder specifications are believed to be working fairly well with most unmodified asphalt binders in controlling low temperature thermal cracks in asphalt pavements, they do not work as well for certain types of asphalt binders including physically and chemically modified asphalt binders. For this reason, a simple test method, the Asphalt Binder Cracking Device (ABCD), is proposed to characterize the low temperature properties of asphalt binder. The objectives of this study are to develop an ABCD test system and test procedures that provide accurate and repeatable low temperature characteristics of asphalt binders and to validate the ABCD test system by comparing its results with low temperature field performance data.

The ABCD uses the dissimilar coefficients of thermal expansion/contraction of asphalt binders and metals, to directly determine the cracking temperature of asphalt binders. As shown in Figure 1, the ABCD consists of a hollow cylindrical invar (a low thermal expansion Ni-Fe alloy) ring with a uniform thickness and an electrical strain gauge glued to the inside of the ring and a flexible silicone mold. A resistive temperature detector (RTD) is also glued to the inside of the ring to closely monitor the specimen temperature. The asphalt binder is molded onto the outside of the ABCD ring. A flexible silicone mold is used to form the asphalt binder into a ring shape.

Asphalt binders have much larger coefficients of thermal expansion/contraction ($170\text{-}200 \times 10^{-6} /^{\circ}\text{C}$) than the invar ($1.4 \times 10^{-6} /^{\circ}\text{C}$). As the temperature drops, the differential thermal contraction will cause development of tensile thermal stress in asphalt and eventual thermal cracks. Strain in the metal tube caused by the thermal stress will be measured by the electrical strain gauge and used to calculate fracture stress of the asphalt binder. When the specimen cracks, the accumulated thermal stress is relieved and will be shown as a sudden drop in the strain reading as shown in Figure 2. The cracking temperature of the asphalt binder is directly determined as the temperature where the sudden drop of measured strain occurs.

Using various modified and unmodified asphalt binders, the repeatability of ABCD test was studied. For unmodified binder, the standard deviation of a single ABCD test was less than 1.0°C and some polymer modified binders, the standard deviation was slightly larger than 1.0°C .

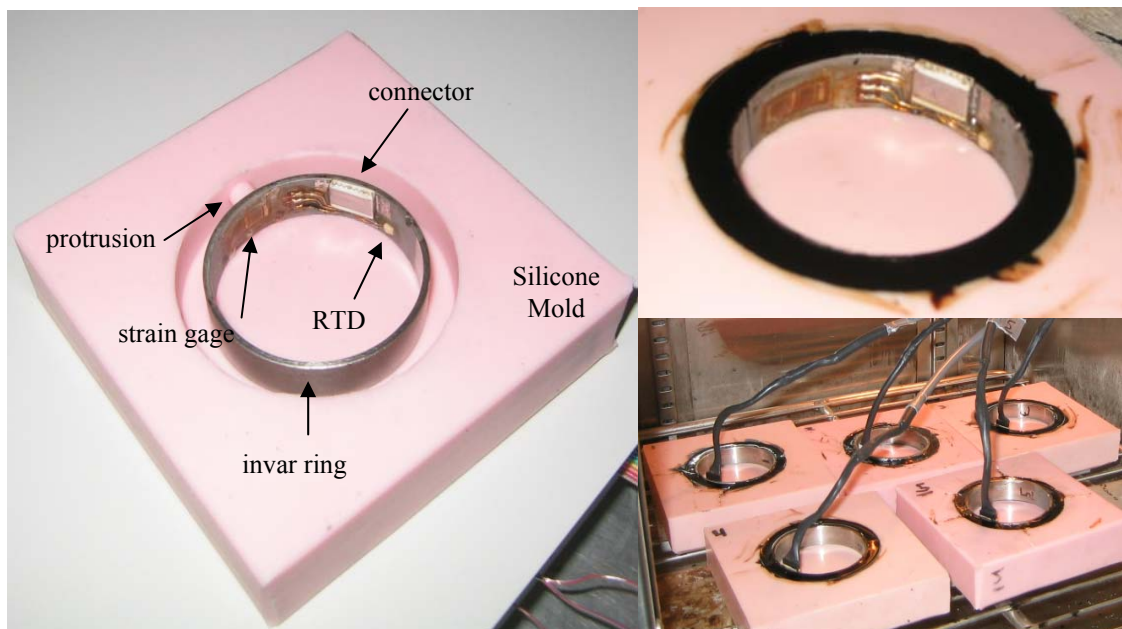


FIGURE 1 The latest version of Asphalt Binder Cracking Device (ABCD): Empty invar ring in the silicone mold (left) and ABCD rings with binder sample (right).

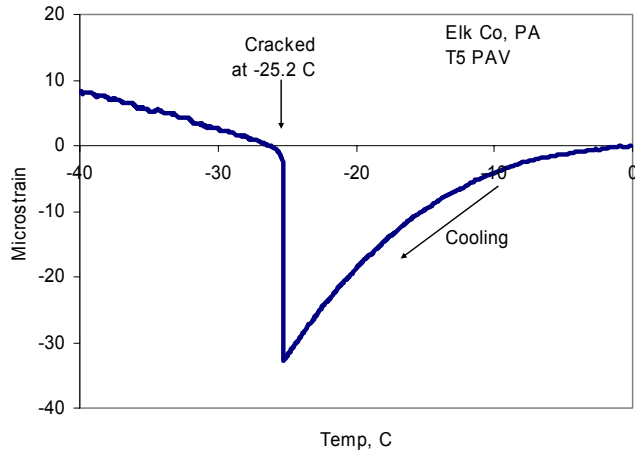


FIGURE 2 A typical ABCD test result.

The ABCD test was found to be sensitive to the addition of polymer to the asphalt binder. As the styrene-butadiene-styrene polymer (used in this study) concentration increases, the binder’s fracture strength increases while the ABCD cracking temperature decreases. This finding agrees well with field observations that asphalt test pavements constructed with polymer modified asphalts have performed better than unmodified companion test pavements regarding low temperature cracking.

In the laboratory validation, ABCD cracking temperatures of various modified binders and unmodified binders were compared with the results of the thermal stress restrained specimen test (TSRST). ABCD showed the better correlation than AASHTO M320 specifications with the TSRST results.

In the field validation study, ABCD cracking temperatures correlated consistently better with crack severities of Elk County Test Road, Lamont Test Road, and Highway 17 SPS 9A sections in Ontario than AASHTO M320 critical temperatures. The summary of the field validation is given in Table 1.

The final version of the ABCD test system and test procedure is forgiving for minor errors made during specimen preparation and testing. Unless specimen geometry is defective near the location where the thermal crack is to be developed, ABCD cracking temperature is repeatable.

TABLE 1. Coefficient of Determination (R^2) of Critical Temperature versus Cracking Index of Test Pavements using ABCD and standard AASHTO methods.

Test Road	ABCD	AASHTO M320 Table 1	AASHTO M320 Table 2
Elk Co, PA	0.94	0.21	0.95
Lamont	0.92	0.79	0.76
Highway 17	0.80	0.92	0.56

CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

The low temperature thermal cracking of asphalt pavements is one of the main causes for annually repeating expensive highway repairs. The successful development of a standard asphalt binder specification is the key to eliminating the premature failure of asphalt pavement due to low temperature thermal cracking, since the cracking phenomenon is primarily an asphalt binder dependent problem. The current Association of American State Highway and Transportation Officials (AASHTO) M320 Table 1 binder specification was developed as a product of the Strategic Highway Research Program. While AASHTO M 320 Table 1 is believed to be working fairly well with most unmodified asphalt binders, it does not work as well for certain types of asphalt binders including physically and chemically modified asphalt binders. For this reason, an alternative asphalt binder specification (AASHTO M320 Table 2) was recently adopted. In the alternative specification, the low temperature properties of an asphalt binder are characterized using both Bending Beam Rheometer (BBR) and a strength test such as Direct Tension Tester (DTT). The stiffness and m-value from BBR are used to calculate thermal stress in the binders as the temperature drops. DTT determines the tensile strength of binder. Then, the cracking temperature is determined as the temperature where the induced thermal stress equals the tensile strength of the binder.

However, the AASHTO M320 Table 2 specification also has several drawbacks, since it does not directly measure the cracking temperature of the asphalt binder. The lengthy analytical procedure requires estimation of the thermal stress development based on several assumptions, such as thermal expansion coefficient of binder, time-temperature shift function, etc. It also requires a large number of tests. The strain rate used in DTT is much faster (orders of magnitude) than the field thermal strain rate. The resulting tensile strength is not repeatable and may not be representative of field strength value.

1.2 OBJECTIVES

An Asphalt Binder Cracking Device (ABCD) is proposed to characterize the low temperature properties of asphalt binder. The objectives of this study are:

1. To develop an ABCD test system and test procedures that provide accurate and repeatable low temperature characteristics of asphalt binders; and
2. To validate the ABCD test system by comparing its results with field performance data.

1.3 INVESTIGATIVE APPROACH

This investigation is divided into three tasks. Upon completion of each task, the results were evaluated to make necessary changes in the study.

- a) Literature Review: A literature review was performed at the beginning of the project to determine if similar concepts have been used to characterize the low temperature performance of asphalt binders.
- b) Development of ABCD: An ABCD test system which produces repeatable results with an easy-to-use procedure was developed. Several variables related to equipment and the test procedures were investigated. Variables related to equipment included wall thickness of ABCD ring, type of material for the measuring device, and sample molds. Variables related to test procedures included sample molding procedure, calibration of the ABCD ring for temperature and load, conditioning temperature, length of conditioning prior to testing, cooling rate, etc. Test results were analyzed and summarized to finalize an optimum test system and test procedure.
- c) Validation of ABCD: Several asphalt binders of various types (straight run, polymer modified, chemically modified, etc.) with known field performance were used for validation of ABCD technique. The results of ABCD tests were compared with the field performance and the critical temperatures determined by AASHTO M320 Table 1 and Table 2 binder grading procedures.

CHAPTER 2 LITERATURE REVIEW

Low temperature thermal shrinkage cracking is one of four major failure modes in asphalt pavement, together with rutting, fatigue cracking, and moisture damage. Thermal shrinkage cracking in asphalt pavement occurs when the thermal tensile stress within the asphalt pavement that results from a temperature drop exceeds its strength at that temperature. Thermal cracks typically appear as transverse cracks (pavement cracks perpendicular to the direction of traffic) at regular intervals in field pavements.

Several different test methods and procedures have been proposed to determine the low temperature cracking potential of asphalt binders. One of the earliest methods to characterize the low-temperature mechanical behavior of asphalt was the Fraass Brittle Point test. The Fraass test has not been widely used, and little or no data exist that can be used to establish a relationship between the Fraass brittle point temperature and asphalt properties (1,2,3).

Consistency and temperature susceptibility were also used as simple measures of low temperature cracking potential. Soft asphalts with a high penetration or low viscosity were thought to perform better at low temperatures. Temperature susceptibility parameters, such as Penetration Index (PI) (4) and Pen-Vis Number (PVN) (5) were considered to be the asphalt properties influencing low temperature cracking.

Based on field experiments later, many researchers recommended limiting stiffness values as a way to control the thermal cracking of asphalt pavements (6,7,8). Asphalt binders or pavements with a high stiffness at low temperatures would develop higher thermal stresses and fracture at warmer temperatures. Because an accurate and easy-to-use measuring instrument was not available, the cracking temperature or the limiting low temperature stiffness of asphalt binder had been extrapolated from consistencies measured at higher temperatures, such as penetrations at 5 and 25°C, viscosity at 25°C, or the ring-and-ball softening point (50-60°C) (3,9).

The currently used Association of American State Highway and Transportation Officials (AASHTO) M 320 Table 1 binder specification was developed as a product of the Strategic Highway Research Program (10,11). In the specification, asphalt binder is graded based on its performance characteristics (Performance Graded or PG grading system). For example, PG 70-22 asphalt binder has a low potential for rutting at pavement temperatures below 70°C and will not crack at pavement temperatures above -22°C. Low-end temperatures for PG grades are determined from the Bending Beam Rheometer (BBR) and/or the Direct Tension Tester (DTT). BBR tests are performed at a low test temperature by loading a simply supported prismatic asphalt binder specimen at mid-span with a constant load. The deflection at the mid-span is recorded as a function of time. Stiffness is calculated as a function of the applied load, measured deflection, and specimen geometry, then plotted against time on a log-log scale. To meet the M 320 Table 1 low temperature specification limit, the asphalt binder must have a stiffness less than 300 MPa and a m-value (slope of log[time]-log[stiffness] plot) larger than 0.300 at 60 second loading time and at a specification temperature plus 10°C (for example, for PG X-22 grading, the test is conducted at -12°C). The m-value is related to the relaxation time of the asphalt binder. An asphalt binder with a high m-value will relax quickly and prevent the rapid accumulation of thermal stress. In certain conditions, the low temperature limit is determined by DTT failure strain. When tested at a specification temperature plus 10°C, the passing minimum failure strain is 1.0%, a failure strain considered to be the criteria for a ductile-brittle transition. Asphalt binder with high failure strain is considered to be ductile and will have better resistance to thermal cracking.

Although the stiffness and m-value criteria in AASHTO M 320 Table 1 perform fairly well with most unmodified asphalt binders, they do not work well for certain types of asphalt binders including physically and chemically modified asphalt binders. For this reason, an alternative asphalt binder specification (AASHTO M 320 Table 2) was recently adopted. The alternative specification requires that the critical temperature for the thermal cracking of an asphalt binder be determined using both BBR and DTT tests. The stiffness and m-value are used to calculate the thermal stress in the binders and DTT is used to determine the tensile strength of the binder. The temperature where the calculated induced thermal stress equals to the tensile strength of the binder is referred to as the critical temperature.

Calculation of thermal stress is lengthy and complex (12). Using BBR tests at two or three temperatures, a creep stiffness master curve is constructed and then converted into a relaxation modulus. The temperature dependency of binder is also determined from the BBR tests by assuming that the temperature dependency follows the Arrhenius function. The coefficients of thermal expansion/contraction (α) of asphalt binders are assumed to be all equal with the value of $170 \times 10^{-6}/^{\circ}\text{C}$. Then the thermal stress is expressed as a convolution integral as follows:

$$\sigma(\xi) = \int_0^{\xi} E(\xi - \xi') \frac{\partial(\varepsilon - \varepsilon^{th})}{\partial(\xi)} d\xi' \quad (2.1)$$

where,

- $\sigma(\xi)$ = thermal stress at reduced time ξ , MPa
- ξ = reduced time, s
- ξ' = time, dummy integration variable, s
- E = relaxation modulus of asphalt binder, MPa
- ε = mechanical strain
- ε^{th} = $\alpha \cdot \Delta T$, thermal strain

Bahia et al. (13) recommended that the tensile strengths of asphalt binders be determined at combinations of five temperatures and four strain rates. Because of poor repeatability of DTT, six identical specimens are tested and the average of the highest four values is used as the strength value at each temperature and strain rate. This means that a large number of DT tests may be required to define the tensile strength envelope over the critical temperature range. These tests are in addition to several BBR tests required to estimate the thermal stresses.

Another approach to determine the cracking temperature of asphalt binder uses the Thermal Stress Restrained Specimen Test (TSRST) procedure. This procedure was originally developed to determine cracking temperature of the asphalt mixtures. In the TSRST procedure, a specimen is glued to the two metal platens of a test system and enclosed in an environment chamber. The specimen is then cooled at a certain rate while contraction of the specimen is restrained by applying controlled tensile load. The experiment continues until the specimen fails in tension or reaches the peak load. Roy and Hesp (14) successfully used the TSRST procedure to determine the critical temperatures of notched asphalt binders.

Iliuta et al. (15) and Hesp (16) reported significant discrepancies between performance of binders used in several Canadian pavement trials and prediction based on AASHTO M320 Table 1 and 2. Physical hardening was believed to significantly influence the low temperature field performance. Based on these observations, an asphalt binder grading procedure based on fracture mechanics was developed. From notched bending tests or notched tension tests at various temperatures, ductile-brittle fracture transition temperature was determined

There is no reliable direct laboratory method to determine the temperature where asphalt binder cracks due to thermally induced stress when thermal contraction is constrained as it is in asphalt pavement. The current AASHTO M 320 specifications do not directly measure cracking temperature of asphalt binder. They rely on oversimplification of binder rheology and/or an unreasonably large number of tests. Furthermore, strain rates used in DT test are orders of magnitude faster than field thermal strain rates. Thus, the resulting DTT tensile strengths may not be representative of field strength.

CHAPTER 3

ASPHALT BINDER CRACKING DEVICE (ABCD)

The Asphalt Binder Cracking Device (ABCD) uses the dissimilar coefficients of thermal expansion/contraction (CTE) of asphalt binders and metals to directly determine the cracking temperature of asphalt binders. As shown in Figure 3.1, ABCD consists of a hollow cylindrical metal ring with a uniform thickness and an electrical strain gauge glued to the inside of the ring. A temperature sensor is also glued to the inside of the tube to closely monitor the specimen temperature. The asphalt binder is molded onto the outside of the ABCD ring as shown in Figure 3.2.

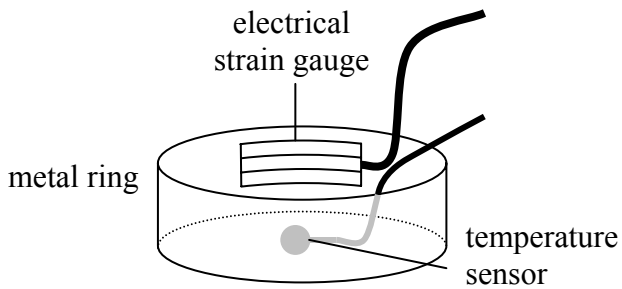


FIGURE 3.1 Asphalt Binder Cracking Device (ABCD) consists of 2 in. (O.D.) x ½ in. (H) hollow metal ring, electric strain gage, and a temperature sensor mounted on the ring.

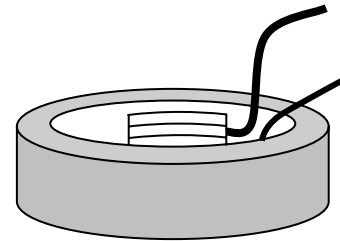


FIGURE 3.2 Asphalt binder molded onto the ABCD ring.

3.1 OPERATING PRINCIPLE

Asphalt binders have much larger coefficients of thermal expansion/contraction ($170\text{--}200 \times 10^{-6} / ^\circ\text{C}$) than do metals ($1.4\text{--}24 \times 10^{-6} / ^\circ\text{C}$). As the temperature drops, the differential thermal contraction (more rapid contraction of asphalt binder than metal) will cause development of tensile thermal stress in the asphalt and eventual thermal cracks. Strain in the metal ring caused by the thermal stress can be measured by the electrical strain gauge and used to calculate fracture stress of the asphalt binder. When the specimen cracks, the accumulated thermal stress is relieved and will be shown as a sudden drop in the strain reading. The cracking temperature of the asphalt binder is directly determined as the temperature where the sudden drop of measured strain occurs. Details of theoretical developments and the testing procedures are discussed in the following sections.

3.2 THEORETICAL CONSIDERATION OF THERMAL CRACKING OF ASPHALT PAVEMENT

Thermal stress development in asphalt binder in field pavement versus that in the ABCD test device is compared in the following sections.

3.2.1 Orthotropic Response of Asphalt Pavement Cooling and Length Factor

As temperature drops, asphalt pavement behaves differently in three mutually perpendicular directions as shown in Figure 3.3. In the vertical direction, there is no restraint and all thermal strain is realized as contraction leaving no thermal stress (pavement gets thinner and free of stress in the vertical direction). In the longitudinal direction (direction of traffic), pavement is restrained from contraction and thermal strain causes developing thermal stress (pavement maintains the same length and is in state of tensile stress). In the transverse direction (perpendicular to the direction of traffic), it is speculated that pavement is restrained from contraction by friction between pavement and underlying layer. Some of thermal stress may be relieved by slip (pavement contracts some and is in state of lower tensile stress than in longitudinal direction).

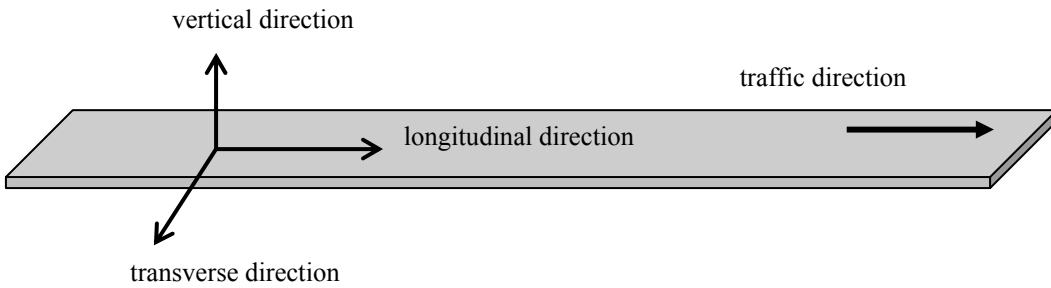


FIGURE 3.3 Directions considered in thermal contraction of asphalt pavement.

For this reason, considering the stresses in the longitudinal direction is most important in determining the critical temperature of asphalt binder in the field. Asphalt cement concrete consists of, by volume, 83-85% of aggregates, 10-12% of asphalt binder, and 4-5% of air voids. If the pavement is assumed to be composed of 85% aggregate volume and 15% asphalt binder volume (volume ratio of 5.7:1) and air voids are ignored for simplicity, a one-dimensional ratio in the longitudinal (traffic) direction between aggregate and binder can be calculated for simplified ideal packing with unit cubic volume as shown in Figure 3.4. In this simplified model, the pavement is made up of small cubic cells, each containing a cube of aggregate nestled in one corner and filling 85% of the cell with the remaining 15% of the space occupied by the binder.

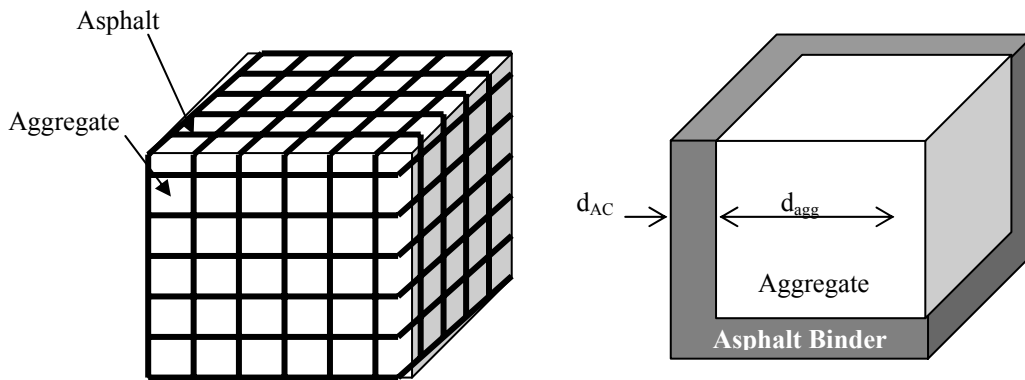


FIGURE 3.4 Idealized packing of aggregate and asphalt binder and 3-D cubic phase diagram.

The volume fraction of aggregate in the phase diagram is $d_{agg}^3 = 0.85$ and, thus, $d_{agg} = 0.9473$ ($\sqrt[3]{\text{volume fraction of aggregate}}$) and $d_{AC} = 1 - d_{agg} = 0.0527$. The one-dimensional ratio of aggregate to binder is defined as length factor (LF) and is about 18 for a typical asphalt mixture with 15% void in mineral aggregate (VMA).

3.2.2 Mechanical Strain of Asphalt Binder in the Field

As the temperature slowly drops, the aggregate and asphalt binder both contract. However, majority of tensile strain will develop in the binder due to its relatively low modulus and viscoelastic nature (flow). The asphalt film aligned parallel to the direction of traffic (longitudinal direction) will not crack because total strain on asphalt binder is smaller than that in the plane perpendicular to the direction of the stress, which receives additional strain due to contraction of aggregate. The change of total strain of the mix due to cooling is in two parts, thermal contraction and elastic elongation due to thermal stress, both occurring simultaneously. For an instantaneous temperature drop ΔT , the mechanical strain on the asphalt binder is:

$$\varepsilon_{AC-load} = (\alpha_{AC} + 18 \alpha_{agg}) \Delta T - 18 \varepsilon_{agg-load} \quad (3.1)$$

where,

α_{AC} = coefficient of thermal expansion of asphalt binder, typically $171-200 \times 10^{-6}/^{\circ}C$

α_{agg} = coefficient of thermal expansion of aggregate, typically $2-8 \times 10^{-6}/^{\circ}C$

ΔT = instantaneous temperature drop, $^{\circ}C$

$\varepsilon_{agg-load} = \frac{P}{A \cdot E_{agg}}$ = mechanical tensile strain of aggregate due to thermal load P

$\varepsilon_{AC-load} = \frac{P}{A \cdot E_{AC}}$ = mechanical tensile strain of asphalt binder due to thermal load P

A = cross sectional area of asphalt binder and aggregate, and

E_{agg}, E_{AC} = elastic modulus of aggregate and glassy modulus of asphalt binder, respectively

In other words, the mechanical tensile strain of asphalt binder in the field can be expressed with two separate terms as in Equation 3.1;

- 1) induced thermal strain resulting from contraction of asphalt binder and contraction of aggregate, and
- 2) strain relieved by elongation of aggregate due to thermal load P.

3.2.3 ABCD Test with Uniform Cross-Section Specimen

The larger thermal contraction of asphalt binder relative to the metal ABCD ring causes compression in the ring. Some of this thermal strain of the asphalt binder is relieved by thermal contraction of the ABCD ring and compression due to thermal load acting on the ABCD ring. Static equilibrium requires that load induced by thermal contraction of asphalt binder should be equal in asphalt binder and ABCD ring. Further, for an instantaneous temperature drop ΔT , total elastic deformation (elongation of asphalt binder and compression of the ABCD ring due to load P') is ($\varepsilon_{ABCD-load} + \varepsilon_{AC-load}$) and should equal the difference of thermal contractions, $(\alpha_{AC} - \alpha_{ABCD}) \cdot \Delta T$. The relationship can be solved for the mechanical tensile strain of asphalt binder.

$$\varepsilon_{AC-load} = (\alpha_{AC} - \alpha_{ABCD}) \Delta T - \varepsilon_{ABCD-load} \quad (3.2)$$

where,

α_{ABCD} = CTE of the ABCD ring; 1.4, 12, and $24 \times 10^{-6}/^{\circ}C$ for invar, steel, and aluminum, respectively

$\varepsilon_{ABCD-load} = \frac{P'}{A_{ABCD} \cdot E_{ABCD}}$ = mechanical compressive strain of the ABCD ring due to thermal load P'

A_{ABCD} = cross sectional areas of ABCD ring

The mechanical tensile strain of asphalt binder in the ABCD test also can be expressed as two separate terms as in the equation 3.2;

- 1) induced thermal strain resulting from differential contraction of asphalt binder and ABCD ring, and
- 2) strain relieved by compression of ABCD due to thermal load P'.

CHAPTER 4 MATERIALS AND TEST METHODS

4.1 MATERIALS

4.1.1 Materials Used for Repeatability Study

Two groups of asphalt binders were used for the repeatability study: 2 PG binders and 12 roofing binders.

Canadian PG binders

Two PG binders were obtained from Imperial Oil of Canada; PG 58-28 and PG 70-28, both RTFO-PAV aged. The PG 70-28 was polymer modified with Styrene-Butadiene-Styrene (SBS) and the PG 58-28 was an unmodified binder. The critical cracking temperatures based on AASHTO M 320 Table 1 criteria were -30.1°C and -31.0°C for PG 58-28 and PG 70-28 binders, respectively, with the m-value as the controlling criteria for both. When reaching a stiffness of 300 MPa, the critical temperatures were -31.0°C and -35.0°C for the PG 58-28 and PG 70-28 binders, respectively. These two binders were used to establish the repeatability of the ABCD test.

Roofing binders

Roofing binders were also used to study repeatability of ABCD. These 12 roofing binders (5 coatings and 7 fluxes) were used for two reasons. First, unlike RTFO-PAV aged binders which are very labor intensive to prepare, roofing binders are readily available in massive quantities from suppliers. The first stage of the repeatability study using round aluminum molds and aluminum rings consumed about one gallon each of the RTFO-PAV aged PG 70-28 and PG 58-28 binders. Because the continuation of the project required many more binder specimens, it was decided to use more economical and easily obtainable roofing binders for the initial development and refinement of ABCD procedures and verify them with the aged paving binders at the later stage. Second, these roofing binders represent two extremes of consistency of asphalt so any workability issues in specimen handling, preparation, and testing with ABCD could be examined; the coatings were much stiffer than aged paving grade asphalt binders while the fluxes were much softer than unaged paving binders.

4.1.2 Materials Used for Laboratory Validation

FHWA Binders Used for Polymer Modified Binder Study

To compare the ABCD with current test methods, 12 asphalt binders being studied by the Federal Highway Administration (FHWA) were obtained and tested with the ABCD. As shown in Table 4.1, the type of the FHWA binders are flux, unmodified base (PG 64-28), unmodified high grade (PG 70-22), air-blown, styrene-butadiene-styrene (SBS) linear grafted, styrene-butadiene-styrene (SBS) linear, styrene-butadiene-styrene (SBS) radial grafted, ethylene vinyl acetate (EVA), ethylene vinyl acetate (EVA) grafted, ethylene styrene interpolymer (ESI), chemically modified crumb rubber asphalt (CMCRA), and AASHTO Materials Reference Library #191 binder. The term 'grafted' indicates there was a chemical reaction between the polymer and the asphalt binder. Eight of the binders were modified with various methods, and ten of them were tested with the thermal stress restrained specimen test (TSRST). Results were published in FHWA-RD-02-074 report (17). Together with Superpave Binder Tests (AASHTO M 320), TSRST results were used in evaluating ABCD results. TSRST was tested according to a provisional AASHTO standard test method (AASHTO TP10-93) and is considered to be one of the laboratory methods for evaluating the thermal crack potential of asphalt mixtures (18).

TABLE 4.1 Description of Binders Obtained from FHWA

FHWA ID	Description
B6224	flux
B6225	unmodified base (PG 64-28)
B6226	unmodified high grade (PG 70-22)
B6227	air-blown
B6229	styrene-butadiene-styrene (SBS) linear grafted
B6230	styrene-butadiene-styrene (SBS) linear
B6231	styrene-butadiene-styrene (SBS) radial grafted
B6232	ethylene vinyl acetate (EVA)
B6233	ethylene vinyl acetate (EVA) grafted
B6243	ethylene styrene interpolymer (ESI)
B6251	chemically modified crumb rubber asphalt (CMCRA)
AMRL 191	AASHTO Materials Reference Library #191

SBS Binders with Varying Concentration

To study the effects of polymer concentration, five asphalt binders were formulated in an asphalt supplier’s laboratory to have 0, 2, 3, 4, and 5% SBS concentrations. The base binder was PG 40-40. At 5% SBS concentration, the modified binder was graded as PG 70-34 following AASHTO M 320 Table 1 specification. Pertinent PG grading test data were provided by the supplier and summarized in Table 4.2.

TABLE 4.2 PG Grading of SBS Modified Binders with Varying Concentration

SBS, %	Low Temperature Critical Temperature, °C					DT Stress @ Fracture, MPa			DT %Strain @ Fracture		
	PG Grade	M320 T1 High	M320 T1 Low	BBR S	BBR m-value	-24°C	-30°C	-36°C	-24°C	-30°C	-36°C
0.0	40-40	44.5	-41.5	-41.5	-43.0		4.56	2.31		1.02	0.42
2.0	52-40	53.1	-41.7	-41.7	-41.9	3.33	4.55		0.76	0.60	
3.0	52-40	57.4	-41.4	-42.3	-41.4		4.41	3.52		1.03	0.46
4.0	58-34	63.3	-39.3	-42.0	-39.3	4.12	4.93		6.79	1.04	
5.0	70-34	70.0	-38.1	-42.2	-38.1	3.96	5.09		6.22	1.45	

4.1.3 Materials Used for Field Validation

Elk County Test Road

In 1976, six AC-20 asphalt binders from different sources were used to construct six test pavements at Traffic Route 219 in Elk County, Pennsylvania, to study low temperature performance and durability (19). The project was well documented and the low temperature performance of the pavements was measured using Cracking Index (CI). CI is a total number of equivalent full-width cracks per 152.5 m (500 ft) section. Samples of these six asphalts were saved for later studies. During SHRP, the saved asphalt samples were used to validate TSRST and later again used to validate the M-320 Table 1 specification (18,20). The remaining asphalt samples (ranging from 100 to 400 grams) were used to validate the ABCD. Complete detailed information on these six asphalt binders (labeled as T1 through T6) is given in references 8, 19, and 20; the properties pertinent to this investigation are given in Table 4.3. Four months after construction, the T1 and T5 test pavements cracked with recorded minimum air temperature of -29°C. Four years after construction, T2, T4, and T6 test pavements cracked with the recorded minimum air temperature of -32.8°C. T3 test pavement never cracked during the seven year test period.

TABLE 4.3 Properties of AC-20 Asphalts Used in Elk County Pennsylvania Test Road

Asphalt Type	Crude Sources	Method of Refining	Cracking Index after 4years	TSRST Fracture Temp, (°C)	M-320 Table 1 Critical Temp, (°C)	
					RTFO	PAV
T1	49% Sahara, 21% W. TX, 21% MT, 9% KS	Vacuum Distillation and Propane Deasphalting	92	-19.3	-22	-18
T2	66.7% TX Mid-Cont., 33.3% Arabian	Steam Distillation	9	-22.7	-28	-17
T3	85% Light Arabian, 15% Bachaquero	Vacuum Distillation	0	-24.0	-28	-26
T4	75% W. TX Sour, 25% TX and LA Sour	Vacuum Distillation	12	-25.4	-26	-23
T5	Same as T1	Vacuum Distillation and Propane Deasphalting	64	-19.8	-24	-22
T6	Blend of Heavy Venezuelan and Middle East Crude	Vacuum Distillation	7	-26.9	-30	-28

Lamont Test Road

Together with the Elk County Test Road, the Lamont Test Road was used in field validation of AASHTO M320 Table 2 specification (12). The test road was built in 1991 near Lamont, Alberta as a full-scale test road for Canadian Strategic Highway Research Program (C-SHRP). The detail of the test road was described in a report prepared by EBA Engineering Consultants (21). Its 12 year performance monitoring records were prepared by Gavin et al. (22). Of 7 binders used in the Lamont Test Road, 5 binders were obtained and tested with ABCD.

Highway 17 near Petawawa Ontario

The Highway 17 test sections were constructed during 1996 and 1997 near Petawawa Ontario as part of SPS-9A program. The asphalt binders used in these test sections include modified binders with styrene-butadiene copolymer. The binders from these test sections were also used to develop a fracture mechanics-based binder grading method in a study conducted at Queen's University and the University of Minnesota (16).

4.2 ABCD TEST SYSTEM

Initially, ABCD rings made out of aluminum were used together with aluminum molds to verify the concept. The preliminary test results showed that the ABCD was very sensitive to polymer modification and produced very different results than the current asphalt binder grading system did. However, the repeatability of this initial set-up was proved to be poor. New ABCD rings made out of invar and silicone molds used for later ABCD set-ups provided much improved repeatability. The following sections describe the final configuration of the ABCD test system components and test procedures used in this study.

4.2.1 ABCD Rings

To verify the concept of the proposed test device, aluminum, steel, and invar ABCD rings with dimensions of 50.8-mm (outside diameter) x 12.7-mm (height) x 1.65-mm (thickness) were made. Each ring was instrumented with 350-Ohm general purpose electrical strain gauges commonly used in experimental stress analysis. Originally, the strain gauges were directly soldered to lead wires which became cumbersome during sample preparation and were

easily damaged. To solve these problems, snap-on connections were glued inside the rings next to the gauges. Later, the connector was mounted with thin metal foil and spot-welded to the ring as shown in Figure 4.1. The ring wall thickness of 1.65-mm was arbitrarily chosen to obtain reasonable strain readings (about $50\mu\epsilon$) at fracture while providing rigidity to the ABCD rings during specimen preparation and handling. A preliminary investigation showed that changing the ring thickness did not affect the ABCD cracking temperature. Based on the results of a preliminary study using ABCD rings made from these three different metals, invar ABCD rings were chosen for the final test system and used for lab and field validation studies.

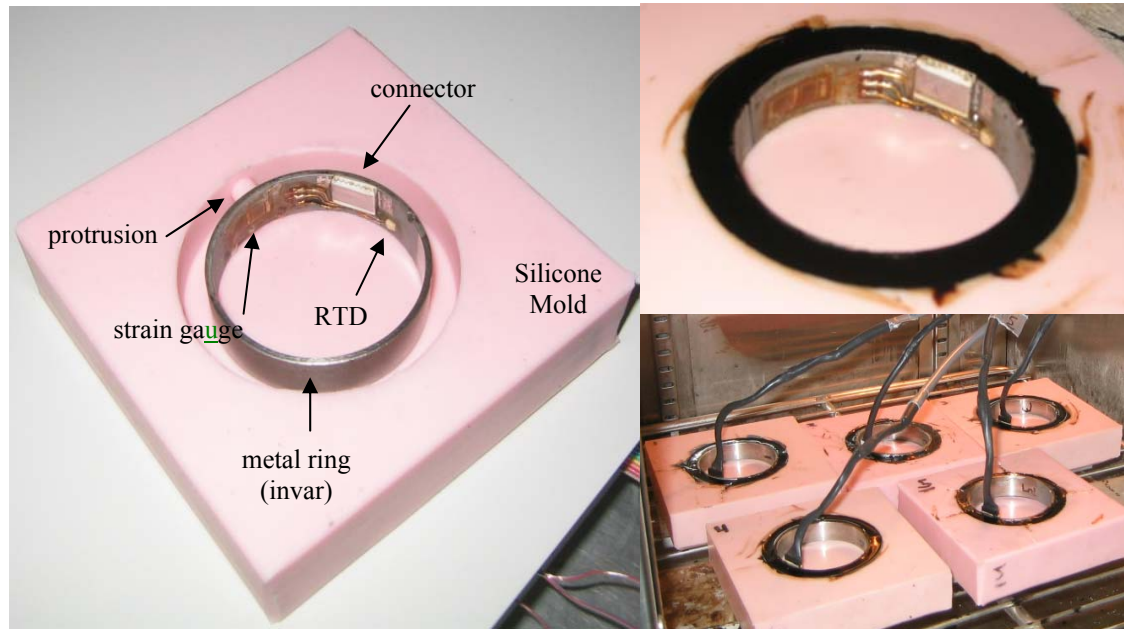


FIGURE 4.1 The latest version of Asphalt Binder Cracking Device (ABCD): Empty invar ring in the silicone mold (left) and ABCD rings with binder samples (upper and lower right).

4.2.2 Specimen molds

Aluminum Molds

Aluminum molds were used in the initial configuration to produce uniform 6.35 mm thick circular asphalt binder specimens on the outside surface of the ABCD ring. As shown in Figure 4.2, the mold consisted of a 10.2 cm square base plate, a 47.5 mm diameter centering plate with 3.18 mm thickness, and two mold halves with 12.7 mm thickness. The centering plate was precisely located on the top of the base plate with two dowel pins. Each half of the mold was secured to the base plate with two shoulder bolts.

Silicone Molds

One piece silicone molds were made by casting liquid silicone rubber into another mold that formed the base, centering plate, and a 6.35 mm diameter cylindrical protrusion at the center height. This protrusion created a hole in the asphalt samples to decrease its cross-sectional area and to induce a crack. Two different types of silicone rubber were used; a stiff rubber with shore hardness number of 45 and a soft rubber with shore hardness number of 30 (Figure 4.3). Lower shore hardness corresponds to greater flexibility of the silicone. Originally, there were two protrusions at the opposite sides. This resulted in not being able to determine which side the crack will occur. This caused a problem since strain gauges that are adjacent to the protrusions do not always pick up the strain relief accurately when the specimen fractures at the opposite sides. For this reason, the silicone mold was redesigned to have only one protrusion.



FIGURE 4.2 Aluminum molds (left), aluminum mold with a trimmed binder specimen.



FIGURE 4.3 ABCD silicone molds flexible (left) and stiff (right). In the final version of these molds, only one of the two protrusions has been retained.

4.2.3 Environmental Chamber and Data Acquisition System

A programmable environmental chamber was used to cool the asphalt specimens. The chamber holds up to six test specimens on a single shelf and provides uniform cooling and heating rates. At the beginning of the development, specimen temperature was measured from two thermocouples imbedded in a dummy specimen placed next to the test specimens. Later, it was found that there was about 2°C temperature variation within the environmental chamber which contributed to the variability of ABCD results. To reduce this variability, an RTD was mounted on the inner surface of each ABCD ring to measure the temperature of each test specimen separately.

The latest version of the data acquisition system has five signal-conditioning strain gauge channels and five RTD channels. LabVIEW software and a computer were used to record time, temperature, and strain every ten seconds from each sample.

4.3 SAMPLE PREPARATION

The binder was heated in tins for one hour in order to be sufficiently fluid to pour. The AASHTO binder specifications for BBR and DT recommend a minimum pouring temperature that produces a consistency equivalent to that of SAE 10W30 motor oil (readily pours but is not overly fluid) at room temperature. PAV samples were degassed with a vacuum oven for 15 minutes to remove entrapped air at the pouring temperature. An aluminum foil spout was wrapped around the tins which were placed in a steel cup to slow heat dissipation when pouring several samples shown in Figure 4.4. The steel cup acts like a heat reservoir and holds temperature well. It was especially useful when preparing roofing binders which tends to stiffen very quickly due to their high consistency.



FIGURE 4.4 Pouring sample from steel cup with aluminum foil spout.

The silicone molds were prepared by applying a release agent of talc and glycerol (with a 1:1 mass ratio) to the specimen forming surfaces. The coating was applied with a small paint brush to produce a thin uniform film to prevent bonding with the mold. The outside and bottom of the rings were also coated and then seated in the mold making sure it was level with the top. The strain gauge was positioned next to the protrusions in order to accurately measure the fracture strain.

The hot asphalt binder was poured into the mold starting at one spot, letting the binder reach the top and then move around the mold in a single pass. It was poured in a continuous stream as quickly as possible to avoid a drop in temperature and to avoid entraining air bubbles or gaps. The mold was slightly overfilled to compensate for binder shrinkage during cooling. After allowing the entire assembly to cool at ambient temperature (25°C or lower) for 30-60 minutes, the excess binder was trimmed flush with the top of the mold using a heated spatula.

The edges of the silicone molds were gently bent to break any adhesion between the silicone mold and the binder specimen, and then the ring was carefully twisted to separate the ring from the sample to release any bonding. The rings would release easily if they were well coated with the release agent, and no deformation was caused to the sample. After breaking the bonds, the binder sample remained inside the silicone mold until the sample fractured, ending the test.

The aluminum molds used in the initial set-up required more steps due to the four-piece assembly. First, the base was covered with release plastic film that was cut from transparency sheets. Then, the two halves of the mold were bolted to the base and the centering plate was attached with two dowel pins. The inside of the mold was also lined with plastic and coated with release agent. The rings were coated as well. The rings were covered with small tin lids to prevent binder from spilling inside.

The hot asphalt binder was poured into the mold starting at one spot, letting the binder reach the top and then move around the mold in a single pass. It was poured in a continuous stream as quickly as possible to avoid a drop in temperature and to avoid entraining air bubbles or gaps. The mold was slightly overfilled to compensate for binder shrinkage during cooling. After allowing the entire assembly to cool at ambient temperature for 30-60 minutes, the excess binder was trimmed flush with the top of the mold using a heated spatula. The aluminum molds had to be conditioned at -20°C for 2-5 minutes in order to stiffen the binder before de-molding. Then they were de-molded by removing the bolts, sliding the mold halves apart, and peeling away the plastic.

4.4 TESTING PROCEDURE

The data acquisition software LabVIEW was opened and the gauges were checked to make sure they were working properly before placing the samples in the environmental chamber at -20°C. A program was then started on the environmental chamber to condition the samples for 30 minutes and begin the cooling process at a constant rate (10°C/hr). These test parameters were chosen based on preliminary test results and practical reasons. The conditioning temperature of -20°C was about 10°C warmer than the warmest fracture temperature observed for the various asphalt binders in this study and the 10°C/hr cooling rate has been most popularly used in many previous studies. In the latest procedure used for field validation, the binder specimens prepared with the silicone molds were placed at +20°C in the chamber and tested without conditioning. From +20°C to -20°C, the cooling rate was 40°C/hour and after that 10°C/hour. This procedure would work better for binders with ABCD cracking

temperatures close to -20°C. The silicone mold and the ABCD ring provide support to the binder sample at the ambient to hot temperatures preventing gravity-induced deformation of soft specimens. The strain and temperature readings were recorded on 10-second intervals. A real-time plot of the strain was monitored and the tests were ended when the samples cracked, producing a sudden jump in strain. The cracking temperature was taken directly from the temperature versus strain plot at the strain jump as shown in Figure 4.5. Two cracked test specimens removed from the ABCD rings after the test and the silicone molds are shown in Figure 4.6. It should be noted that the ABCD cracking temperature of the binder is always lower than the thermal cracking temperature of pavement since the contraction of aggregate causes additional strain to the asphalt binder in the field pavement.

The peak strain at fracture can be used to calculate the average tensile strength of binder at failure. From force equilibrium, the average stress in the binder can be calculated by the following equation;

$$\sigma_{AC} = \varepsilon E_{ABCD} \frac{A_{ABCD}}{A_{AC}} \quad (4.1)$$

where:

σ_{AC} = average thermal stress in the binder

ε = strain on the ABCD ring

E_{ABCD} = Young's modulus of the ABCD ring ($E_{invar} = 141$ GPa)

A_{ABCD} , A_{AC} = cross-sectional areas of the ABCD ring and binder, respectively

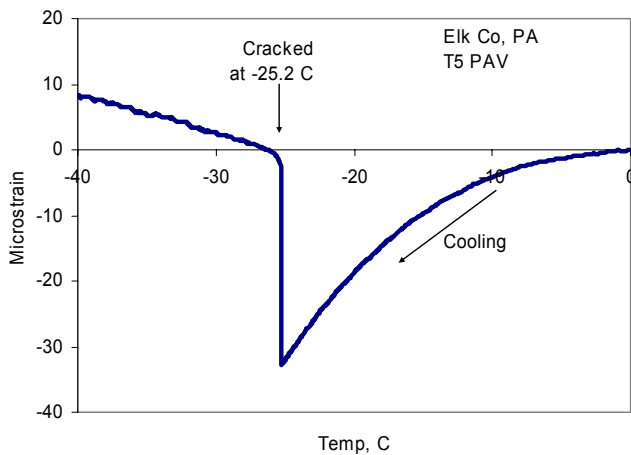


FIGURE 4.5 A typical ABCD test result.



FIGURE 4.6 Cracked test specimens removed from ABCD rings and molds.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 PRELIMINARY INVESTIGATION

5.1.1 Repeatability of Initial Configuration Using Aluminum ABCD Rings and Molds

To determine the repeatability of the aluminum mold-aluminum ring ABCD test, two PAV aged Canadian PG binders were repeatedly tested. The results are given in Figure 5.1. For 43 ABCD measurements of the PG 58-28 binder, the standard deviations of a single ABCD measurement were 0.28 MPa and 2.5°C for fracture stress and fracture temperature, respectively. For 20 ABCD measurements of the PG 70-28 SBS binder, the standard deviations were 1.15 MPa and 4.8°C for fracture stress and fracture temperature, respectively. The variability of aluminum mold-aluminum ring ABCD test was relatively high. The 95 percent confidence intervals of the average ABCD fracture temperature and stress for the PG 58-28 binder were $-38.2 \pm 0.8^\circ\text{C}$ and 1.08 ± 0.09 MPa, respectively. The 95 percent confidence intervals for the PG 70-28 binder were $-48.1 \pm 2.2^\circ\text{C}$ and 2.17 ± 0.66 MPa, respectively. Even though they were graded the same for low temperature performance (-28°C), the SBS polymer modified PG 70-28 cracked at significantly lower temperatures and at much higher stress levels in the ABCD test than did the unmodified PG 58-28.

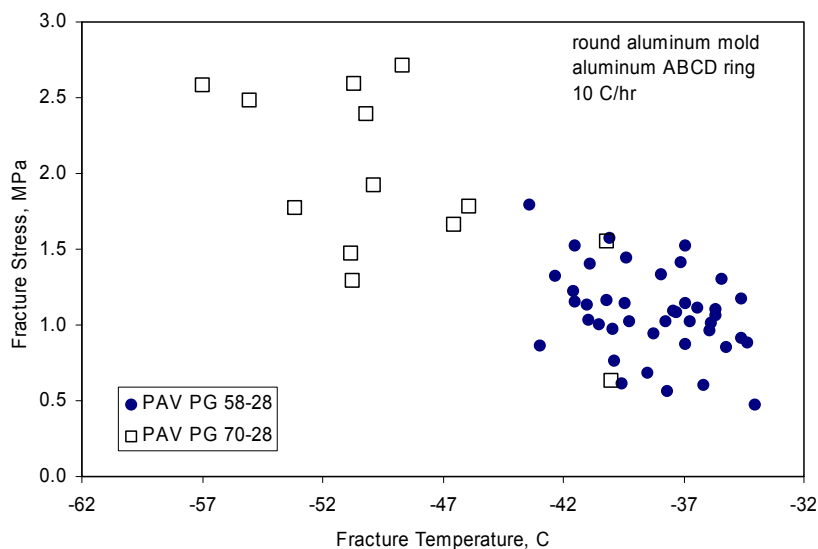


FIGURE 5.1 Fracture temperature versus fracture stress of the two Canadian PG binders determined by aluminum ABCD (round aluminum mold and aluminum ring).

5.1.2 FHWA Binders Tested with Aluminum ABCD Rings and Aluminum Molds

Fracture stresses and temperatures of nine FHWA samples were measured with the round aluminum molds and aluminum rings. Figure 5.2 shows fracture stresses and temperatures of FHWA binders determined by the ABCD. The cracking temperature of each binder varies over a wide temperature range. Their fracture stresses also showed large variability. As the fracture temperature decreases the fracture stress tends to increase for each asphalt. For all binders tested with aluminum mold and aluminum ABCD ring, the fracture strength varied from 0.5 to 4 MPa, with a median of about 2.0 MPa. When ABCD fracture strengths of FHWA binders are compared with strength measured by DTT, no apparent relationship between them was found.

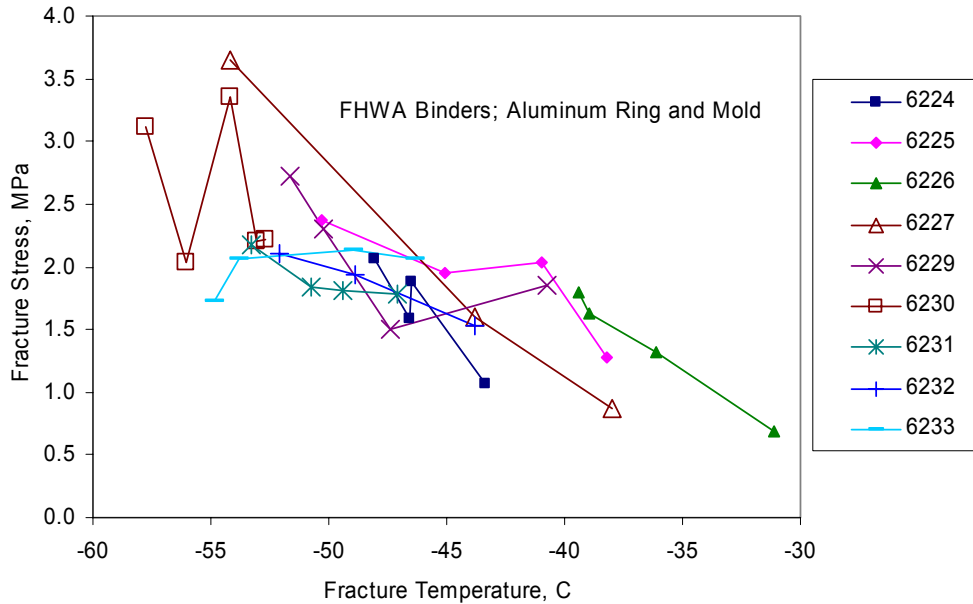


FIGURE 5.2 Fracture temperature versus fracture stress of FHWA binders determined by ABCD (round aluminum mold, aluminum ring).

Ferry (23) explains fracture mechanisms of polymer in terms of temperature regions. Above the glass transition temperature T_g (or at low temperature with very slow rate of loading), polymer chain backbones have an opportunity to reconfigure before the asphalt fails. Viscoelastic relaxation plays a significant role in rupture at this temperature range. Below the glass transition temperature (or somewhat above T_g with very rapid loading), the backbone configuration is immobilized for testing time period and rupture is associated with breaking of primary bonds. The ultimate properties of polymer (fracture strength and strain) are also time- and temperature-dependent as are other viscoelastic parameters. However, fracture strength and strain are not very reproducible since fracture involves not only viscoelastic processes but statistical fluctuations such as microscopic or molecular inhomogeneities. This is why the fracture stress calculated from strength of carbon-carbon primary bonds is always much larger than measured fracture stress. In practical terms, while the operator is perfecting specimen preparation, the fracture strength of the sample may increase. However, fracture test results are still subjected to the effects of random (uncontrollable) conditions, such as location and orientation of microscopic impurities. For this reason, the ABCD measurement suffers a similar repeatability problem that DTT has. However, obtaining near perfect fracture properties in test samples does not have significant practical merit since in the field asphalt binder fractures occur within mixes where many inhomogeneities exist.

To improve the repeatability of ABCD, a controlled inhomogeneity is introduced in the specimen geometry so that the stress at the inhomogeneity may be calculated with reasonable accuracy. Thus a new silicone mold creating a 6.35 mm diameter hole at mid height was developed to improve the repeatability of ABCD test. A comparison between the aluminum molds and the silicone molds is presented later in Section 5.1.4.

5.1.3 Effect of Specimen Thickness

Specimens used to study repeatability had 6.35 mm (1/4 in.) thickness (50.8 mm inner diameter and 63.5 mm outer diameter). Two additional aluminum molds were made to produce specimens with 3.175 mm (1/8 in.) and 9.525 mm (3/8 in.) thickness. PAV aged PG 70-28 Canadian binder was used with aluminum ring (round specimen and 10°C/hr cooling rate) and the results are shown in Table 5.1. As specimen thickness increased, the cracking temperature decreased. For the remainder of ABCD study samples with 6.35 mm (1/4 in.) thickness (50.8 mm inner diameter and 63.5 mm outer diameter) were used.

TABLE 5.1 Effect of Specimen Thickness on ABCD Cracking Temperature (PG 70-28, Aluminum Ring, Round Specimen, 10°C/hr)

	Thickness of Specimen		
	3.175 mm (1/8 in.)	6.35 mm (1/4 in.)	9.525 mm (3/8 in.)
Number of test	4	12	4
Average, °C	-43.6	-47.1	-49.2
Std Dev, °C	4.2	4.8	1.1

5.1.4 Effects of ABCD Ring and Mold Type

The PAV aged PG 58-28 and PG 70-28 Canadian binders were used to study effects of three different rings (invar, steel, and aluminum) and mold materials (stiff silicone mold with Shore Hardness Number, SHN=45, soft silicone mold with SHN=30, and aluminum mold with flat edge) in cracking temperature and repeatability of ABCD. The silicone molds stayed flexible at temperatures below -60°C and the presence of the silicone mold surrounding the test specimen was believed to have a negligible effect on the test results. To validate this assumption, silicone molds were made so that the mold was directly in contact with the ring instead of the asphalt in between. The molds and invar ring were then cooled and the strain was monitored to see what influence the silicone molds had when compared to the strain of an empty ring. It was observed that both the stiff (SHN of 45) and soft (SHN of 30) silicone molds did not have measurable effect on the strain of the rings.

Results of ABCD tests using two Canadian PG binders, various ring and mold types are summarized in Table 5.2. Typical coefficients of thermal expansion (CTE) for invar, steel, and aluminum are 1.4, 12, and 24 x 10⁻⁶ m/m/°C. As shown in Figure 5.3, the invar rings produced the highest cracking temperature because of its very small CTE, which causes almost complete restraint during cooling. The aluminum and steel rings shrink along with the asphalt to provide strain relaxation and, therefore, crack at lower temperatures. The invar rings were also completely machined to precise in dimensions while the aluminum and steel rings were cut from tubing. This resulted with the invar having a lower standard deviation. From Table 5.2, the combination of invar rings and the stiff silicone molds provided the closest cracking temperature compared to the PG grading and the smallest standard deviation of approximately 1.0°C. The average strain jump (ϵ_{jump}) is the amount of strain that the sample releases when it cracks. The rings were positioned so that the strain gauge was placed next to the hole in the sample.

TABLE 5.2 Effects of Mold Type and Ring Type on ABCD Cracking Temperature and Repeatability

Ring Type	Mold Type	Ave. Crack Temp., °C	Std. Dev., °C	Average ϵ_{jump} , $\mu\epsilon$	Number of Trials
PG 58-28 PAV					
Aluminum	Stiff Silicone	-32.98	0.47	35	5
	Soft Silicone	-33.18	1.83	33	4
Steel	Stiff Silicone	-31.81	0.97	24	6
	Soft Silicone	-34.74	1.17	21	3
Invar	Stiff Silicone	-30.55	0.96	21	5
	Al-Flat Edge	-33.92	2.80	79	4
PG 70-28 PAV					
Aluminum	Stiff Silicone	-42.95	1.38	90	6
	Soft Silicone	-46.10	1.35	78	4
Steel	Stiff Silicone	-41.56	1.13	44	4
	Soft Silicone	-47.28	1.09	53	4
Invar	Stiff Silicone	-39.02	1.06	37	5
	Soft Silicone	-41.52	1.07	35	4
	Al-Flat Edge	-46.64	1.85	199	4

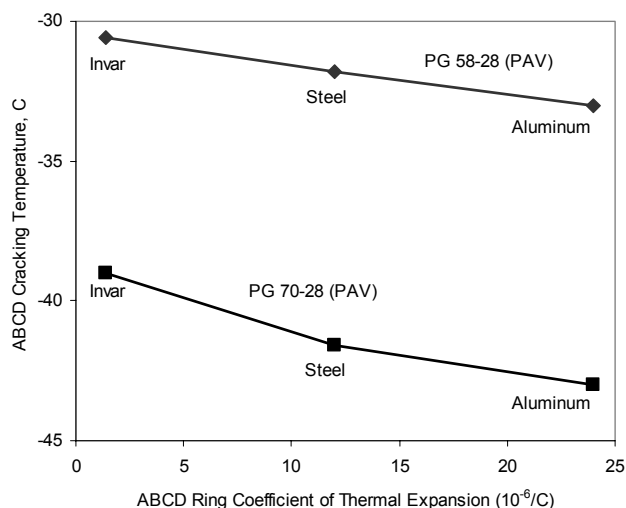


FIGURE 5.3 Effects of CTE of ABCD rings on cracking temperature.

At the ABCD cracking temperature, both stiff and soft silicone molds stayed flexible. However, a difference between them was observed; the specimens in stiff silicone molds cracking an average of 3.0 °C warmer than the soft silicone molds. The stiff silicone molds resulted in a standard deviation range of 0.47 to 1.38 and the soft molds had 1.09 to 1.83. A possible reason for the soft molds having a larger standard deviation is their greater flexibility which increases the likelihood of sample deformation while handling the molds. Consequently, it was decided to use only stiff silicone molds (SHN 45) for the remainder of this investigation.

The silicone molds greatly improved repeatability because the samples always cracked through the holes as shown in Figure 4.6. It was found that samples prepared with the aluminum molds were more sensitive to imperfections caused by trimming, small air voids when pouring, or most likely from handling the samples when demolding. This caused the asphalt to crack randomly at or near an imperfection, which resulted in a greater standard deviation in cracking temperature. Whereas the cracking location is predetermined in the silicon molds so if care is taken in the area of the protrusion, the asphalt is less susceptible to defects from sample preparation. Another advantage to the silicon molds was that they reduce preparation time by 30 minutes by eliminating mold assembling/disassembling steps. Cleaning the silicon molds is also much easier than cleaning the aluminum molds.

5.1.5 Stress Distribution in Asphalt Specimens with Silicone Mold

The stress distribution in the fracture surface of the asphalt samples was estimated from a thick-walled hollow cylinder analysis and considering the stress concentrated at a small circular hole in an infinite plane under uniaxial load (24). This assumes that asphalt is an isotropic and linear-elastic material at low temperatures, which has been accepted in the literature as a reasonable estimate. The normalized stress distribution is shown in Figure 5.4. Stresses at the four corners are based on an average stress of 1.0 MPa. A maximum stress develops at the inside edges of the hole, next to the ring with a stress concentration factor of 2.02. In this analysis, the parts of silicone protruding inside of the asphalt binder specimen are assumed to be flexible at all test temperatures and their effects on binder stress development are ignored.

5.2 LABORATORY VALIDATION USING SILICONE MOLD AND INVAR ABCD RING

5.2.1 Repeatability of ABCD with Roofing Binders

The repeatability of the ABCD test using the silicone mold and invar ring on the two Canadian PG binders was within an acceptable range, about 1°C standard deviation. Investigation of repeatability of the new ABCD

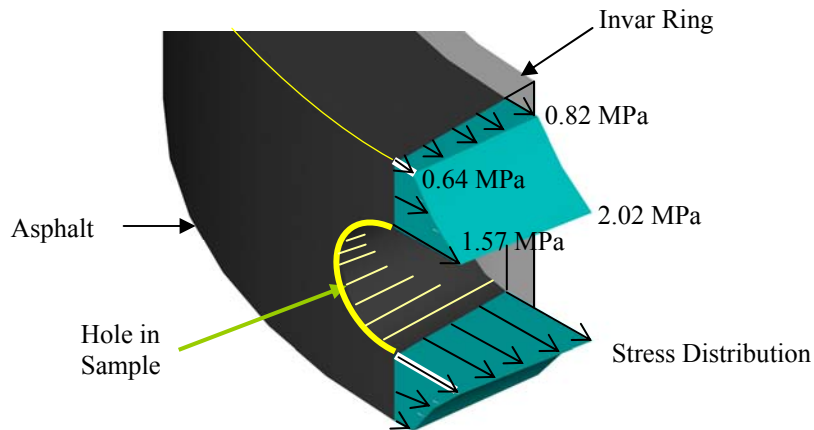


FIGURE 5.4 Three dimensional circumferential stress distribution of asphalt binder specimen prepared with silicone mold (average stress = 1.00 MPa).

procedure using silicone mold and invar ring was continued with roofing binders. Twelve unmodified roofing binders from the Asphalt Institute were each tested two times with the invar ring and stiff silicone mold (02-061 coating was tested four times). Five of the binders were of a coating grade (penetration 10 or lower) and seven were a flux grade (penetration 200-300). The testing of coating and flux binders covers a wide range of consistencies. The flux samples only had to be heated to 150°C in order to be sufficiently fluid to pour and the coating samples required to be heated to 240°C. For both fluxes and coatings, there was no problem in preparation and performing the ABCD tests. The results given in Table 5.3 show good repeatability with an average standard deviation of 0.65°C. Currently, there is no low-temperature cracking specification for roofing binders, so a critical temperature comparison cannot be made.

5.2.2 ABCD (Silicone Mold and Invar Ring) Test Results of FHWA Binders

For the silicone mold and invar ring ABCD tests, twelve asphalt binders (RTFO-PAV aged) were prepared and supplied by Dr. Shenoy of FHWA Turner Fairbank Highway Research Center. Duplicate ABCD tests were performed on each binder. The fracture temperatures and fracture stresses are given in Table 5.4. Ten of these

TABLE 5.3 Roofing Binder Results from Invar ABCD and Stiff Silicone Mold

	ID	ABCD Cracking Temperature, °C			Std. Dev. °C
		Trial 1	Trial 2	Avg	
Coating	02-059	-28.5	-28.5	-28.5	0.0
	02-061 (1)	-31.3	-33.1	-32.2	1.3
	02-061 (2)	-32.2	-32.9	-32.6	0.5
	02-129	-21.8	-23.5	-22.7	1.2
	02-130	-25.8	-26.9	-26.3	0.8
	02-209	-28.6	-29.4	-29.0	0.5
Flux	02-058	-47.0	-47.9	-47.5	0.7
	02-060	-40.7	-40.9	-40.8	0.1
	02-129	-37.9	-39.8	-38.9	1.4
	02-130	-35.9	-37.1	-36.5	0.8
	02-206	-38.3	-41.6	-40.0	2.3
	02-207	-39.7	-39.8	-39.8	0.1
	02-210	-38.1	-39.8	-38.9	1.3

Table 5.4 Cracking Temperatures FHWA Binders Determined by ABCD and Other Methods.

ID	Description	FHWA-RD-02-074 Report						ABCD Cracking Temperature			
		M320 Tab 2 (°C)	M320 Tab 1 (°C)	S (°C)	m (°C)	TSRST (°C)	TSRST Strength (MPa)	Trial 1 (°C)	Trial 2 (°C)	Std Dev (°C)	Avg (°C)
B6225	Unmodified base	-28	-28	-28	-30	-26	1.68	-33.4	-27.9	2.7	-30.6
B6226	Unm high grade	-27	-28	-28	-29	-24	2.12	-27.8	-25.4	1.7	-26.6
B6227	air-blown	-28	-28	-30	-28	-27	1.96	-31.7	-33.1	1.0	-32.4
B6229	SBS linear graft	-34	-33	-33	-34	-33	2.31	-39.5	-37.6	1.3	-38.6
B6230	SBS linear	-33	-31	-32	-31	-30	2.11	-37.6	-39.4	1.3	-38.5
B6231	SBS radial graft	-34	-32	-32	-32	-30	2.30	-38.5	-36.7	1.3	-37.6
B6232	EVA	-31	-31	-31	-31	-29	2.79	-35.4	-38.1	1.9	-36.8
B6233	EVA grafted	-33	-31	-32	-31	-31	1.86	-37.3	-41.9	3.2	-39.6
B6243	ESI	-29	-31	-31	-31	-33	2.32	-42.1	-41.9	0.1	-42.0
B6251	CMCRA	-29	-29	-29	-29	-29	1.10	-31.3	-30.1	0.8	-30.7

FHWA binders had been studied and the results were published in the FHWA-RD-02-074 report which contained TSRST results and critical temperatures of binders based on M320 Table 2 specification, limiting stiffness (S), and limiting m-value (m) (17). TSRST tests were also performed on asphalt mixtures prepared by mixing each binder with igneous diabase aggregate.

With the controlled geometrical inhomogeneity of the hole created by silicone protrusion, each binder cracked at narrower ranges of temperature and fracture stress than the uniform cross-section ABCD specimens in aluminum mold-aluminum ring test. Standard deviations of FHWA binders were 0.71 MPa and 0.38 MPa for aluminum ring-aluminum mold ABCD test and invar ring-silicone mold ABCD test, respectively. Figure 5.5 shows the significance of binder strength and polymer modification in thermal cracking. In general, binders modified with polymer possessed higher strength than unmodified binders. In turn, the polymer modified binders with higher strength fractured at lower temperatures than the no-polymer binders with lower strength. Grafted polymer modified binders possess higher strength than their counterparts. For EVA, grafting lowered cracking temperature while for linear SBS modified binder grafting did not change cracking temperature. Fracture stresses and temperatures of all binders including the FHWA binders, the two PG binders from Imperial Oil in Canada, and the 12 roofing binders are presented in Figure 5.6. The roofing fluxes exhibited very low cracking temperatures attributable to their extreme softness. There seemed to be an upper limit of fracture strength for no-polymer binders at 4 MPa when tested with silicone mold and invar ABCD ring and a 10°C/hr cooling rate. The two Canadian PG binders from Imperial Oil (SBS modified PG 70-28 and unmodified PG 58-28) followed the trend shown by FHWA binders. Even though both binders were graded the same following M 320 Table 1 specification, the SBS modified PG 70-28 performed better due to its low stiffness (flexibility) and high strength.

The fracture stress of the ABCD test is compared again with fracture stresses determined by DTT at three different temperatures, as presented in Figure 5.7. No general trend between them can be found. This is believed to be due to the difference in the rate of loading used in the two tests. The rate of loading for DTT is over 2,000 times faster than ABCD test which could have a significant impact on the apparent strength of asphalt binder.

To determine the strength of the relationship among the critical temperatures presented in Table 5.4, correlation coefficients (r) were determined (Table 5.5). The cracking temperature determined by TSRST was considered to be close representation of field conditions and used as basis of comparison. TSRST showed better correlation with ABCD (r = 0.91) than with M320 Table 2 (r = 0.69) or M320 Table 1 (r = 0.86). The correlation with M320 Table 2 was worse than with critical temperature based on BBR stiffness alone, indicating DTT strength data used in M320 Table 2 procedure caused the decline of strength of correlation. The critical temperature from M320 Table 2 procedure using ABCD determined strength data [M320 Tab 2 (ABCD)], instead of DTT results, showed a much improved correlation with TSRST fracture temperature (r = 0.94). M320 Table 2 (ABCD) and ABCD are highly correlated (r = 0.98) indicating theoretical soundness of ABCD procedure. These correlations are plotted in Figures 5.8-9.

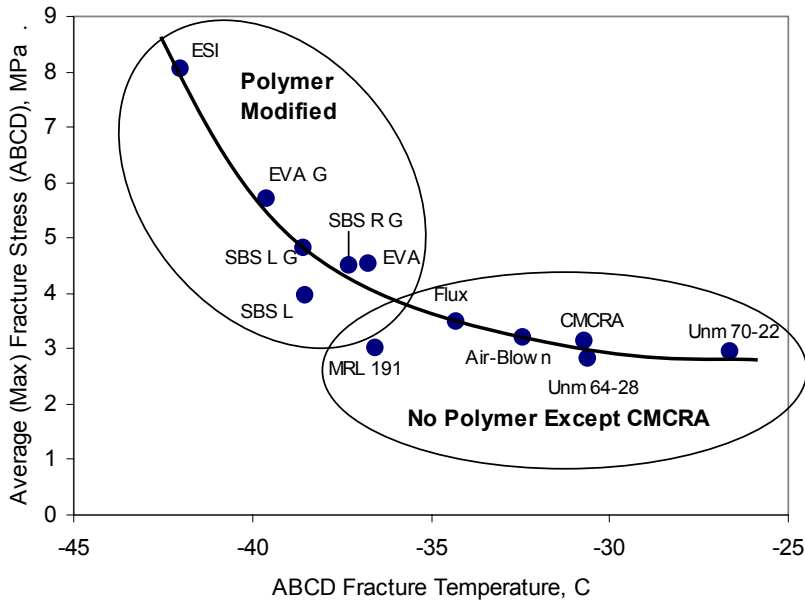


FIGURE 5.5 Fracture temperature versus mean of maximum fracture stress of FHWA binders determined by ABCD using silicone mold and invar ring with cooling at 10°C/hr.

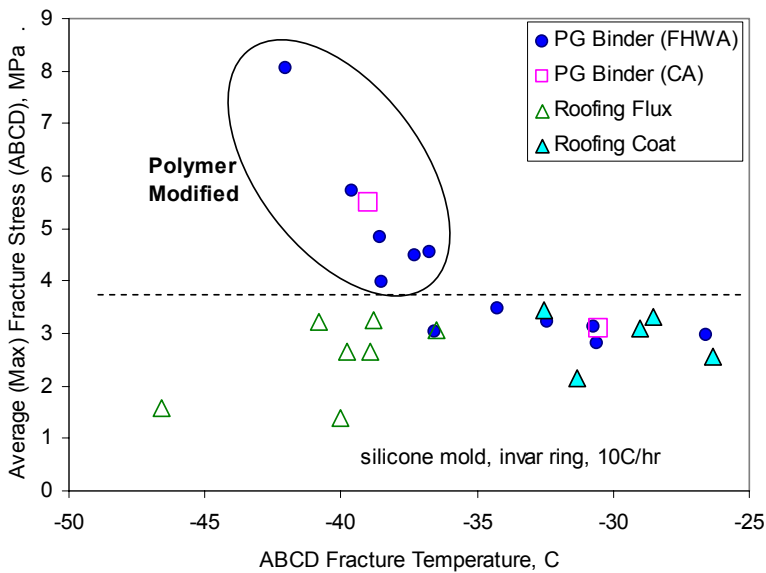


FIGURE 5.6 Fracture temperature versus mean of maximum fracture stress of all binders determined by ABCD using silicone mold and invar ring with cooling at 10°C/hr.

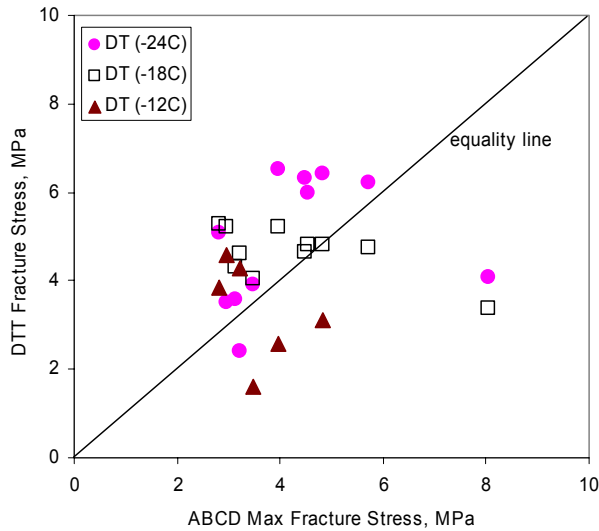


FIGURE 5.7 Comparison of fracture stress of FHWA binders determined by ABCD using silicone mold and invar ring versus those determined by DTT.

TABLE 5.5 Correlation Coefficients among Critical Temperatures (number of data =10)

	ABCD	M320 Tab2 (ABCD) ^a	M320 Tab2	M320 Tab1	S	m	TSRST
ABCD	1						
M320 Tab 2 (ABCD)	0.98	1					
M320 Tab 2	0.71	0.72	1				
M320 Tab 1	0.83	0.85	0.90	1			
S (BBR)	0.87	0.86	0.91	0.92	1		
m-value (BBR)	0.69	0.69	0.82	0.92	0.78	1	
TSRST	0.91	0.94	0.69	0.86	0.84	0.73	1

^a M320 Tab 2 (ABCD): uses strength data from ABCD test instead of DTT

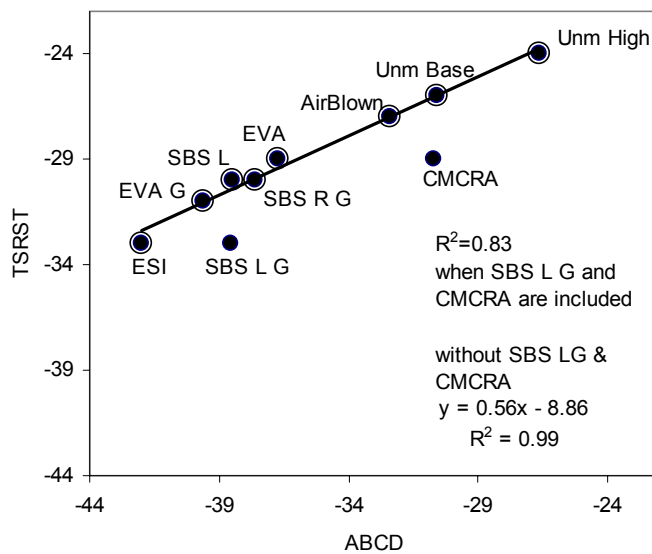


FIGURE 5.8 TSRST cracking temperature versus ABCD cracking temperature.

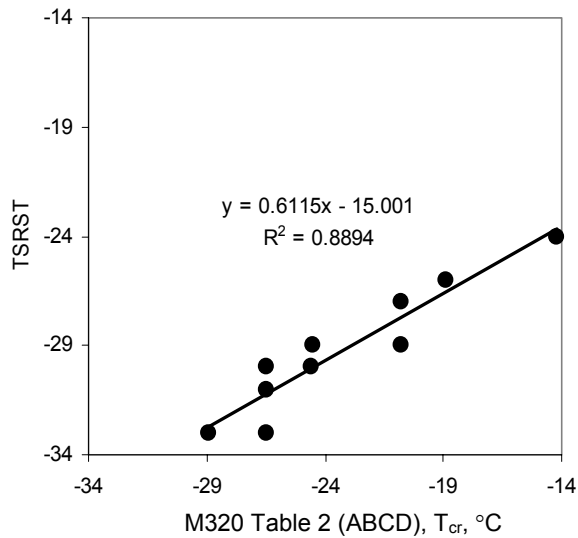


FIGURE 5.9 TSRST cracking temperature versus critical temperature by M320 Table 2 using ABCD strength data.

Stuart and Youtcheff (17) reported ESI being an outlier for the correlation between TSRST fracture temperature and binder cracking temperatures and recommended a further investigation to determine the cause. ABCD test results appear to provide an answer. Unlike the other FHWA binders, ESI showed an extremely high strength in the ABCD test. ESI mix was also the second strongest in TSRST test. However, DTT ranked ESI as the lowest strength among all polymer modified binders. BBR stiffness and m-value criteria of ESI were worse (stiffer) than other polymer modified binders. This made M320 Table 1 predict ESI’s cracking temperature to be warmer than the other polymer modified binders. M320 Table 2 predicts cracking temperature by combining BBR stiffness and DTT strength. The fact that the correlation between M320 Table 2 and TSRST fracture temperature ($r = 0.69$) was worse than the correlation between BBR stiffness and TSRST fracture temperature ($r = 0.84$) suggests that the DTT strength measurement seems inaccurate and needs to be refined. As binders with more diverse strength characteristics are included in paving practice, critical temperature prediction based on thermal stress development alone, such as AASHTO M320 Table 1 using BBR results, will become more inaccurate. A test method or an analysis procedure accounting for both thermal stress development and strength, such as ABCD or AASHTO M320 Table 2 procedure with improved strength measurement, should be used instead to insure reliable prediction of thermal cracking in asphalt pavement.

5.2.3 Effect of SBS Concentration on Low Temperature Cracking

ABCD tests were performed on triplicate samples for each binder and the results are given in Table 5.6 and Figures 5.10-5.11. As SBS concentration increased in the binder, ABCD cracking temperature was lowered. At 5% SBS concentration, ABCD cracking temperature was about 10°C lower than that of the unmodified base asphalt. The increase in SBS concentration also caused an increase in the strength at the time of fracture during the ABCD test, which contributed to lowering the cracking temperature. The strength of the binder containing 5% SBS was 2.4 times stronger than that of the base asphalt. However, the current AASHTO M 320 Table 1 specification indicated that the low temperature performance would be worsened by high concentrations (4 and 5%) of SBS and would not be affected by low SBS concentration levels (2 and 3%). The strength of the binders as measured by DTT was distributed in a narrower range (4.6-5.1 MPa at -30°C). The trend found between ABCD and SBS concentration seems to agree better with field observations. Highway engineers have believed polymer modified asphalt binders enhance performance of asphalt pavements at low temperatures. Recently, the Asphalt Institute (25) compiled low temperature performance data for 138 polymer modified asphalt pavement sections nationwide that had unmodified companion pavement sections. The results are shown in Figure 5.12. In general, polymer modified sections

TABLE 5.6 ABCD Summary of Modified Binders at Various levels of SBS Concentration

Binder	Cracking Temperature, °C					Strength at Fracture, MPa				
	Run 1	Run 2	Run 3	Avg.	Std. dev.	Run 1	Run 2	Run 3	Avg.	Std. dev.
Base	-44.3	-44.8	-43.6	-44.2	0.6	1.6	2.1	0.9	1.6	0.60
2% SBS	-45.3	-47.6	-49.3	-46.5	1.6	2.2	3.1	4.1	2.7	0.61
3% SBS	-47.8	-47.9	-48.2	-48.0	0.2	3.2	2.3	3.3	2.9	0.53
4% SBS	-49.6	-52.3	-51.4	-51.1	1.4	3.5	3.8	2.1	3.1	0.92
5% SBS	-53.8	-55.0	-53.6	-54.1	0.8	5.1	3.2	3.4	3.9	1.03

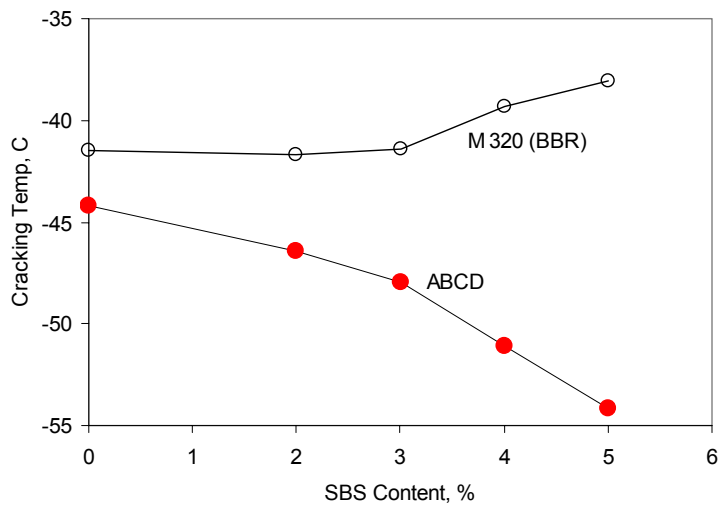


FIGURE 5.10 Effect of SBS concentration on PG low temperature grade (AASHTO M 320 Table 1) and ABCD cracking temperature.

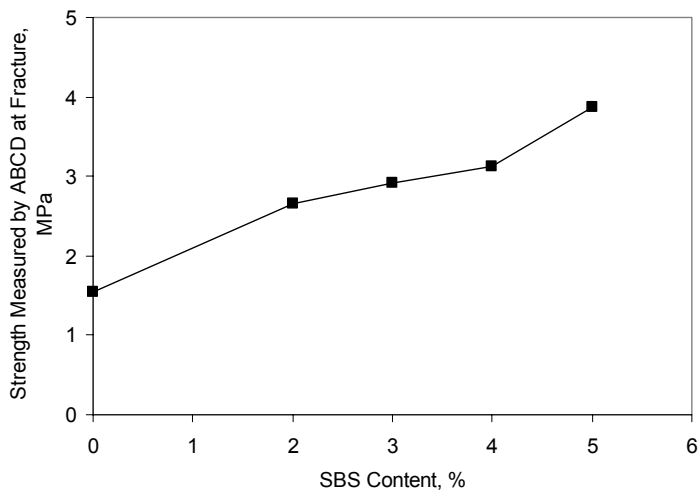


FIGURE 5.11 Effect of SBS concentration on binder strength as measured by the ABCD.

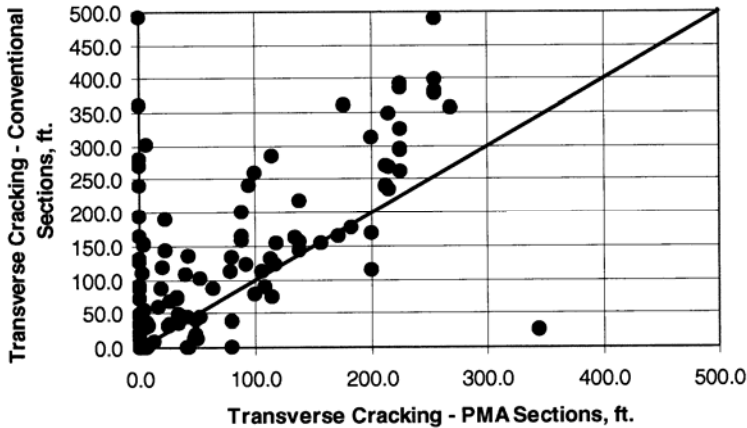


FIGURE 5.12 Length of Cracks Measured on PMA sections versus Companion Sections without PMA (ref 24: Asphalt Institute, Engineering Report 215, page 18, 2005).

developed much less transverse cracking caused by low temperatures than did the unmodified companion sections. No detail about polymer types and PG grades of the modified and unmodified binders was discussed in the report. However, it is well known that SBS and SB were some of most popular polymer modifiers used in test road evaluations. Therefore, it would be reasonable to assume a trend similar to that shown in Figure 5.12 would exist for SBS modified sections. In this field performance study, the pavement sections with polymer modifiers showed significantly less thermal cracking than their unmodified counterparts, suggesting that the ABCD test determines the low temperature performance more accurately than the current AASHTO M 320 specification using BBR data.

5.3 FIELD VALIDATION

ABCD results of asphalt binders used in the three test road projects described earlier are summarized in this section. For these ABCD tests, invar rings and silicone molds were used with 10°C/hr cooling rate. ABCD cracking temperatures were compared with crack severity of test pavements.

5.3.1 Elk County Test Road

At the time of thermal cracking, the degree of binder aging for T1 and T5 would be close to that for RTFO residue and the degree of aging for T2, T4, and T6 would be somewhat between those for RTFO and PAV residues. For this reason, ABCD tests were performed on samples with RTFO and with RTFO/PAV residues. The results are shown in Table 5.7. The post-test inspection of test specimens in the first ABCD trial of samples with RTFO residues revealed that holes in all the specimens were severely deformed. This was due to rotating the ABCD rings back-and-forth about 5 degrees after trimming excessive binder in an effort to break the adhesion bond between the rings and test specimens. RTFO specimens were relatively soft at room temperature and deformed when the insufficiently lubricated rings were turned. The accuracy of the ABCD results for these binders was questionable and a second RTFO residue batch was prepared and tested. By cooling these RTFO specimens at -10°C for 10 minutes before turning the ABCD rings, the problem was avoided. Preparation of RTFO/PAV samples for ABCD test did not require cooling to turn the rings. Despite the problem with the first batch, the results of the first and the second RTFO batches, displayed in Table 5.7, are very close with less than 0.5°C differences on average. ABCD cracking temperatures for RTFO/PAV residues showed strong correlation with the 4-year Cracking Index, with a coefficient of determination, $r^2 = 0.94$ as shown in Figure 5.13. ABCD results of RTFO residues also showed strong correlation with CI with $r^2 = 0.97$. Correlation between M 320 Table 1 critical temperature and 4th year CI was poor ($r^2 = 0.21$) as shown in Figure 5.14. However, when the critical temperatures were estimated based only on BBR stiffness of 300 MPa, correlation with CI was greatly improved with $r^2 = 0.90$.

Table 5.7 ABCD results on RTFO and RTFO/PAV Aged Binders used in Elk County Pennsylvania Test Pavements

ID	ABCD Cracking Temperature, (°C)									
	RTFO (1st Try)			RTFO (2nd Try)				RTFO/PAV		
	1	2	Avg	1	2	3	Avg	1	2	Avg
T1	-21.8	- ^a	-21.8	-21.3	-22.2	-	-21.8	-23.1	-21.7 ^b	-22.4
T2	-34.7	-34.6	-34.7	-34.0	-34.1	-34.4	-34.2	-28.2 ^b	-31.1	-29.7
T3	-33.2	-	-33.2	-	-	-	-	-30.7	-30.7	-30.7
T4	-31.1	-32.9	-32.0	-32.0	-32.5	-	-32.3	-28.5	-29.8	-29.2
T5	-23.2	-26.8	-25.0	-26.0	-25.6	-	-25.8	-25.2	-24.4	-24.8
T6	-33.1	-34.8	-34.0	-33.6	-33.5	-	-33.6	-32.9	-31.6	-32.3
	ABCD Fracture Strength, (MPa)									
	RTFO (1st Try)			RTFO (2nd Try)				RTFO/PAV		
	1	2	Avg	1	2	3	Avg	1	2	Avg
T1	-	-	-	3.1	3.0	-	3.1	3.1	3.0 ^b	3.0
T2	4.9	4.4	4.6	3.2	-	3.5	3.4	2.7 ^b	3.7	3.2
T3	5.4	-	5.4	-	-	-	-	3.5	2.7	3.1
T4	3.1	2.9	3.0	4.2	2.3	-	3.2	3.1	3.6	3.3
T5	2.2	5.0	3.6	3.0	3.7	-	3.3	4.8	3.5	4.1
T6	3.1	4.9	4.0	3.5	4.0	-	3.8	4.5	4.1	4.3

^a not measured ^b thin cross-sectional area at the protrusion caused by improper trimming

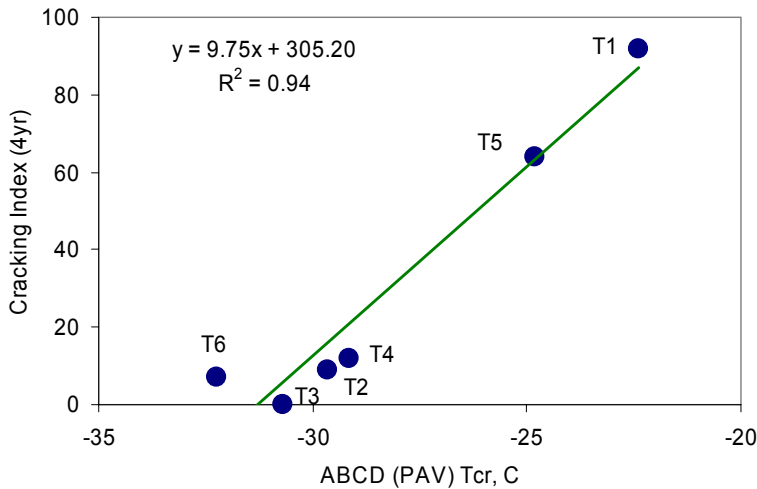


FIGURE 5.13 ABCD cracking temperature versus 4-year cracking Index for Pennsylvania Test Pavements.

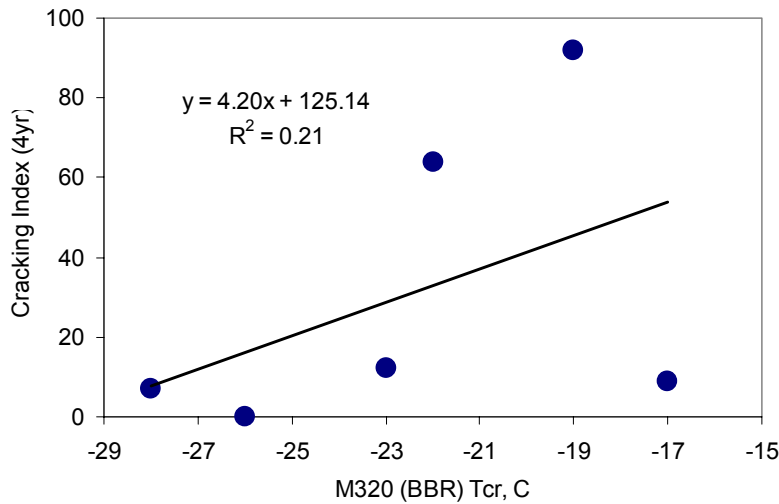


FIGURE 5.14 AASHTO M 320 (BBR) critical temperature versus 4-year cracking Index for Pennsylvania Test Pavements.

5.3.2 Lamont Test Road

The results of ABCD tests on triplicate samples of each available Lamont Test Road binder are given in Table 5.8. The table also includes AASHTO M 320 Table 1 and 2 grades as reported by Bouldin et al. (12). The latest crack survey data completed in 2003 after 12 years of service are also included (22).

The low temperature performance of asphalt binders as measured by number of cracks per one kilometer length of pavement showed good correlation with ABCD cracking temperature measured on RTFO/PAV aged binders (Figure 5.15). However, current AASHTO grading procedures did not show a good correlation as shown in Figures 5.16 and 5.17.

TABLE 5.8 ABCD Results on RTFO/PAV Aged Binders Used in Lamont Test Pavements

Section	Binder	Air Blown	Thermal Crack per km ^a	Critical Temperature, °C					
				M320 ^b	MP1a ^b	ABCD (PAV)			Average
						Run 1	Run 2	Run 3	
1	80/100B	Yes	143	-34.0	-35.5	-- ^c	--	--	--
2	150/200B		180	-31.0	-24.1	-31.7	-32.0	-31.1	-31.6
3	300/400A		0	-38.8	-39.3	-37.7	-39.3	-41.2	-39.4
4	80/100C		163	-27.8	-24.6	-29.3	-29.9	-28.6	-29.3
5	80/100A	Yes	119	-37.5	-31.4	--	--	--	--
6	150/200A		37	-34.8	-35.1	-36.0	-36.6	-35.2	-35.9
7	200/300A		4	-40.0	-35.3	-39.2	-39.6	-37.2	-38.7

^a data from Gavin et al. 2003

^b data from Bouldin et al. 2000

^c no sample available for ABCD test

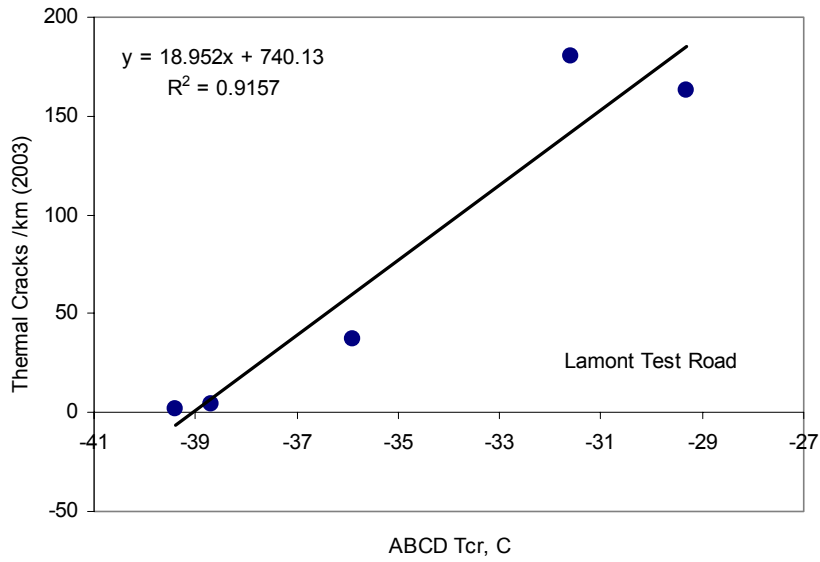


FIGURE 5.15 ABCD cracking temperature versus number of cracks per km in Lamont test pavements.

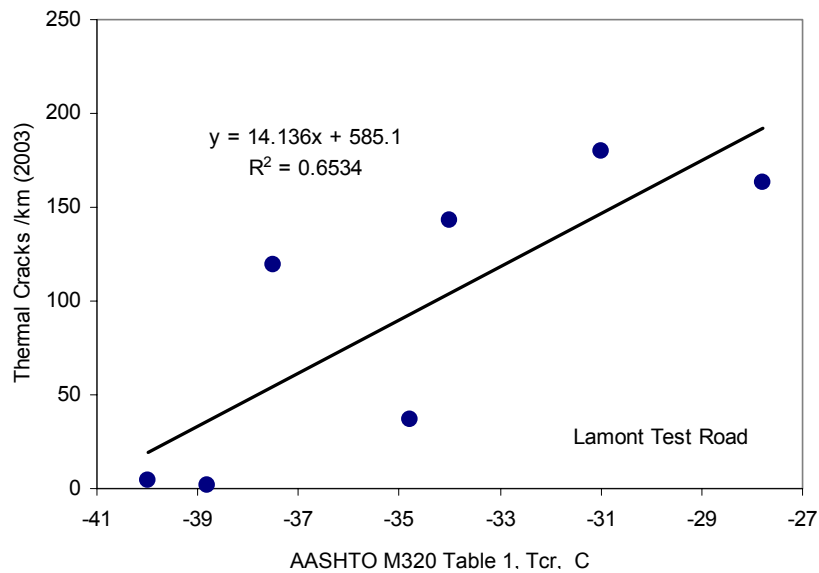


FIGURE 5.16 AASHTO M 320 (BBR) critical temperature versus number of cracks per km in Lamont test pavements.

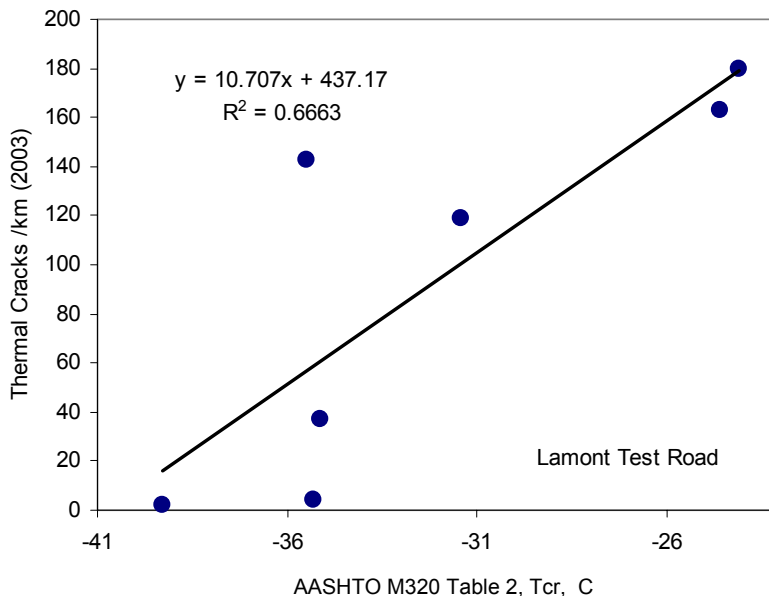


FIGURE 5.17 AASHTO M320 Table 2 critical temperature versus number of cracks per km in Lamont test pavements.

5.3.3 Highway 17 (SPS-9A) near Petawawa Ontario

The results of ABCD tests on triplicate samples of each available Highway 17 binder are given in Table 5.9. The table also includes AASHTO M 320 Table 1 and Table 2 grades as reported by Hesp (16). The latest crack survey data completed in 2003 are also included.

The low temperature performance of asphalt binders as measured by number of cracks per one kilometer length of pavement showed good correlation with ABCD cracking temperature measured on RTFO/PAV aged binders ($r^2 = 0.80$, Figure 5.18). AASHTO M320 Table 2 showed a poor correlation with the number of cracks ($r^2 = 0.56$, Figure 5.19). The best correlation with the crack frequency was shown for AASHTO M320 Table 1 critical temperature determined by BBR data alone (Figure 5.20).

The onset of thermal cracking depends not only on asphalt binder properties but also on many other factors, such as rate of temperature drop, whole pavement structure geometry and composition, traffic, and frost. For some binders used in Highway 17 test sections, the onset of thermal cracking happened at temperatures much warmer than M 320 critical temperatures. Until the 2003 crack survey, Highway 17 sections were subjected to pavement surface temperatures as low as -26.8°C , and two PG 58-34 grade binders cracked. Further, temperatures fluctuated between -26.5°C and -27.2°C for about a week in 2003. Researchers (16) believed that physical hardening, among many others, was a contributing factor to the formation of cracks at higher than expected temperatures. They found that when BBR and DTT were performed after 3 days of isothermal conditioning at the test temperature, instead of the standard one hour, the critical temperature increased by up to 13°C . A binder that is affected more by 3-day physical hardening tends to also be more susceptible to low temperature thermal cracking.

TABLE 5.9 ABCD results on RTFO/PAV aged binders used in Highway 17 test pavements.

Section	Binder	Thermal Cracks per km ^a	Physical Hardening (1h-3d)	Critical Temperature, °C					
				M320-1 ^a	M320-2 ^a	ABCD (PAV)			
						Run 1	Run 2	Run 3	Average
870901	85/100	98		-30		-32.0	-31.1	-32.5	-31.9
870902	PG58-40P	0	4	-41	-39	-47.1	NA ^b	-47.1	-47.1
870903	PG58-34P	65	6	-35	-38	-41.1	-41.1	-40.4	-40.4
870960	PG58-28	169	13	-28	-32	-32.0	-33.6	-32.4	-32.4
870961	PG58-34	52	6	-35	-33	-39.1	-38.7	-40.0	-39.3

^a data from reference 16

^b sample lost due to the presence of an air bubble near the hole

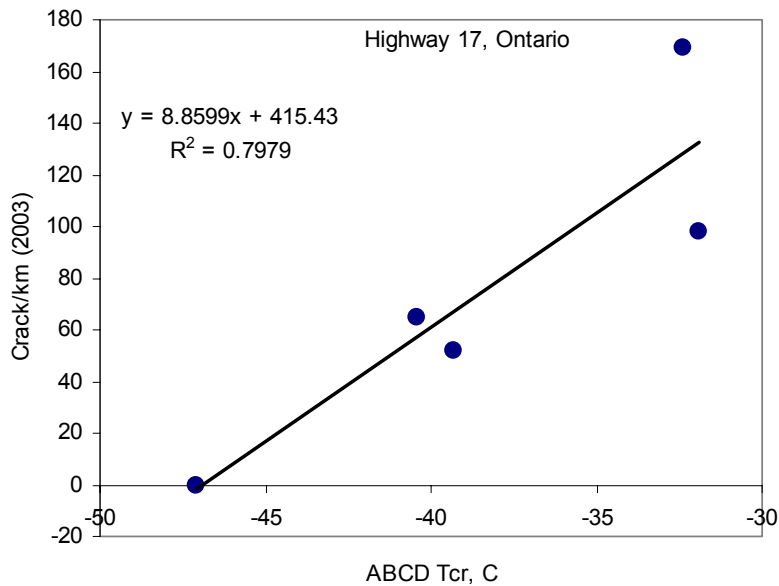


FIGURE 5.18 ABCD cracking temperature versus number of cracks per km in Highway 17 test pavements.

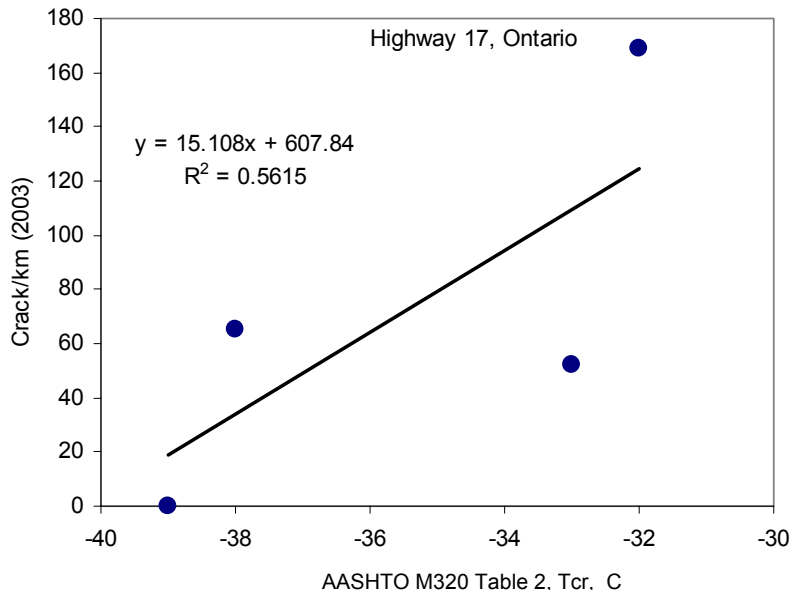


FIGURE 5.19 AASHTO M320 Table 2 critical temperature versus number of cracks per km in Highway 17 test pavements.

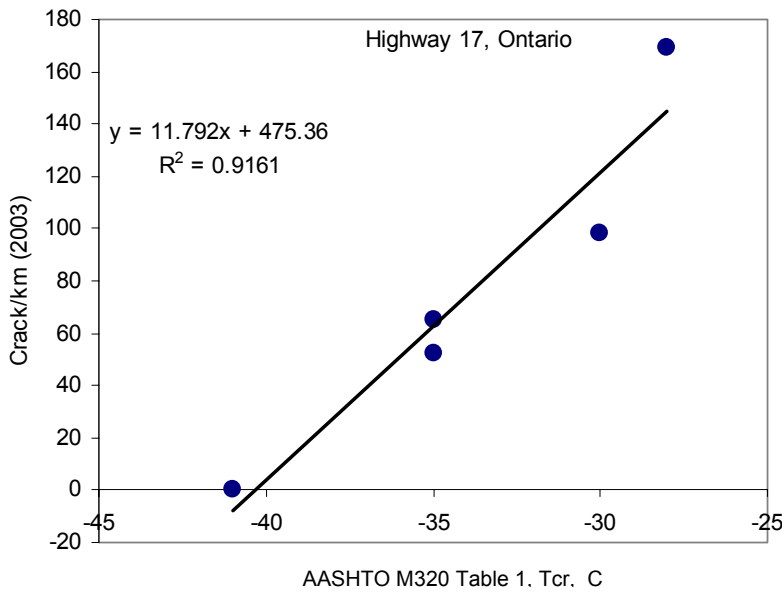


FIGURE 5.20 AASHTO M 320 Table 1 critical temperature versus number of cracks per km in Highway 17 test pavements.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The Asphalt Binder Cracking Device, utilizing the invar ABCD ring and silicone mold with a 6.35-mm protrusion produced repeatable test results in determining the cracking temperatures and strengths of a wide variety of asphalt binders. The ABCD test method is relatively simple and easy in comparison to other existing test procedures. Because the handling of the test specimen by the operator is minimal, there is less opportunity for error. Once the ABCD specimen is trimmed in the silicone mold, the specimen is not disturbed until the test is completed. Another benefit is that several specimens can be tested simultaneously. The current ABCD apparatus used in this study can handle eight specimens per test and can be expanded easily if necessary. Some more specific conclusions of this ABCD study are:

- Use of the invar ABCD ring and silicone mold which produces a 6.35-mm diameter protrusion at mid-height of the binder specimen dramatically reduced the variability of ABCD. For unmodified binders, the standard deviation is 0.9°C and for polymer modified binders, 1.5°C. The standard deviations for the latest ABCD rings with RTD are expected to be even smaller.
- ABCD cracking temperatures of RTFO/PAV residues are most consistently and highly correlated with low temperature performance of all test sections studied.
- The measured relationship between ABCD-determined cracking temperature and change in SBS concentration in asphalt binder is consistent with field observations; the polymer modified test sections outperformed their companion unmodified test sections. The existing AASHTO M 320 Table 1 specification was not able to measure the beneficial effect of SBS addition in asphalt binder.
- For modified asphalt binders prepared from the same base asphalt (FHWA binder), the higher the strength and the lower the cracking temperature. Except the chemically modified crumb rubber asphalt, all polymer modified asphalt had a strength of 4.0 MPa or higher. The strength for all of the no-polymer asphalts including roofing fluxes and coatings was less than 4.0 MPa.
- Thermal Stress Restrained Specimen Test (TSRST), a laboratory mixture test, showed the strongest correlation with ABCD followed by M 320 Table 1 and M 320 Table 2.
- Even though the SBS modified PG 70-28 and the unmodified PG 58-28 from a Canadian supplier were graded the same for low temperature performance level under current AASHTO M 320 Table 1 specification, the SBS modified PG 70-28 cracked at a significantly lower temperature in the ABCD tests than did the unmodified PG 58-28, probably due to its higher tensile strength.
- Effects of isothermal physical hardening may be important to low temperature thermal cracking of asphalt pavement. This phenomenon needs to be further studied using ABCD.

IMPLEMENTATION PLAN

Implementation of the ABCD test method on a wider scale will involve the following steps:

1. The test procedure developed for the ABCD test in this study is prepared in an AASHTO standard format.
2. Prototype ABCDs will be made available to other laboratories for independent evaluation.
3. Continue to work with Ohio DOT, other DOT engineers, and asphalt industry to refine and improve the test.
4. A commercial ABCD test system is being developed through a for-profit company. For current ABCD test, a generic cascading (dual refrigerants) environmental chamber is used. The chamber is heavy (about 300 lb) and noisy when compressor is on. A light (about 50 lb), quiet, compact, and durable integrated system will be built containing and environmental control chamber and a data acquisition system in one device.
5. A funding request submitted to *Highways for LIFE* for refinement of ABCD test procedures and system and commercialization was awarded. A ruggedness test and a round robin test are planned to be completed by December 2009.
6. Technical papers have been published in the *Journal of Materials in Civil Engineering* (2005) and the *Transportation Research Record* (2006).

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