IDEA

Innovations Deserving
Exploratory Analysis Programs

NCHRP IDEA Program

DART Field Validation and Prototype Refinement

Final Report for
NCHRP IDEA Project 193

Prepared by:
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Rao Research and Consulting, LLC

December *2017*

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DART Field Validation and Prototype Refinement

IDEA Program Final Report
Contract Number: NCHRP IDEA 20-30/IDEA 193

Prepared for the IDEA Program
Transportation Research Board
The National Academies

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EXECUTIVE SUMMARY

This report summarizes findings from a National Cooperative Highway Research Program (NCHRP) Innovations Deserving Exploratory Analysis (IDEA) Type 2 study to validate a field-ready prototype of the Duomorph Asphalt Rheology Tester (DART) as a low-cost and easy-to-use asphalt binder testing device. The DART is a piezoelectric sensor-based portable testing system that addresses the need of the paving industry to cost effectively monitor the uniformity or specification compliance of asphalt binder samples at various points along its supply chain. In this study, the research team performed validation tests to determine the effectiveness of the DART in production environments such as a paving job site, a field laboratory, and a binder production facility.

BACKGROUND AND SIGNIFICANCE

Asphalt binders are highly engineered viscoelastic materials that exhibit a range of stiffness values that depend on the temperature and/or frequency at which they are tested. The AASHTO M320 PG specification covers several rheology parameters measured over a range of temperatures and aging conditions an asphalt binder is expected to experience in-service. It takes approximately 2 days in a certified laboratory for an asphalt sample to undergo the entire battery of tests for specification compliance testing. Decidedly, it is not conducive for the entire AASHTO M320 test regime to be used either for quality control (QC) or agency verification on a continuous sampling basis.

Binder properties may change along its journey from its point of production to the paving job site due to various reasons including overheating, tank contamination, steric hardening, or mix modifications. Current practice relies on binder certification by the producer at the point of origination and acceptance by the owner based on this certification. Limited independent verification is performed by the owner primarily due to the time, cost, and resources necessary for testing. This may result in the inability to detect an incorrect binder used during paving.

As a solution to the QC and verification challenges faced by the binder industry, Mallela (2013), Mallela and Carpenter (2000), and Carpenter and Mallela (1996) conceptualized the fundamental science and design of the DART system at the University of Illinois at Urbana-Champaign under NCHRP IDEA funding. Consequently, a bench prototype was developed under a National Science Foundation (NSF)-funded study by Rao, Mallela, Kellner and Sanders (2015). These studies demonstrated the effectiveness of the DART as a rapid testing alternative capable of distinguishing different binder grades and tracking binder consistency under controlled research grade testing environments. This IDEA Type 2 study advanced the technology to a field-ready prototype and validated it in production testing conditions, i.e., in routine QC and quality assurance (QA) at a field laboratory or a hot mix asphalt production plant. This study also enabled “ruggedization” of the DART and improvements to the data processing procedures.

CONCEPT AND INNOVATION

The DART can estimate the viscoelastic properties of the asphalt binder over a good portion of the viscoelastic range of relevance to asphalt concrete performance. The key components of this system are:

1. A circular piezoelectric bending duomorph gauge comprising of a stainless steel disc sandwiched between two other concentrically placed lead zirconate titanate (PZT) piezoceramic discs.
2. An electronic subsystem to (a) electrically activate the sensor, (b) measure the resulting gauge responses, and (c) store the response data for further processing.
3. Software to control gauge activation and data processing to provide the desired outputs.
4. A finite element analyses-based algorithm to calculate material properties indicative of in-situ performance.

The response of this gauge can be measured at different frequencies both in air and in the binder material. The gauge needs to be immersed in binder liquid to measure its response in the material, where measurements can be made over a range of temperatures and frequencies. The gauge’s response in the binder relative to its response in air serves as an indicator of the viscoelastic properties of the binder material. At each target temperature, after thermal equilibrium of the binder sample is reached, the test can be completed in approximately 2 minutes. To obtain a temperature sweep, the gauge response data is collected and processed as the binder material cools from about 150ºF to 70°F. Figure 1 shows binder testing with DART.

BINDER CONSISTENCY CHECK ON FIELD

Binder consistency/uniformity check involves two steps, fingerprinting a certified binder and verification of a sample binder's consistency against the fingerprint of the certified binder. The procedure is as follows:

I. Fingerprinting Certified Binder:
   - i. Measure DART response in air at set frequencies (0–100 Hz), which takes about one minute.
   - ii. Measure the DART response in a certified binder sample at different temperatures at set frequencies.
     - a. Test between a temperature range from 150°F to 70°F in 5°F decrements (cooling), which takes about one minute at each temperature. Cooling from 150°F to 70°F takes at least two hours.
   - iii. Establish a unique "fingerprint" for each certified binder sample.
     - b. The fingerprint of a binder has two parts for each temperature-frequency combination: (1) the ratio of DART's strain in binder to that in air (2) the difference in it's phase shift in binder and in air.

II. Checking Binder Consistency or Verifying Binder Grade in the Field:
   - i. Generate a fingerprint for the random/field sample.
   - ii. Statistically compare the random/field sample fingerprint with a pre-established fingerprint of a certified binder with known characteristics.

Figure 1. DART prototype for field testing and binder testing setup.

ACCOMPLISHMENTS AND BREAKTHROUGHS

This Type 2 IDEA study validated the DART's ability to match same PG grade binders from different sources as well as its ability to distinguish binders of different grades. Next, this study validated the effectiveness of the DART in routine QA using binder samples from construction projects in two different States and from an asphalt mix production facility. From the first Department of Transportation (DOT), samples were collected from QA testing of the two grades used in the State, PG76-22 and PG67-22. DART testing identified the failure of a sample that did not meet the AASHTO M320 requirement for the sample aged in the Pressure Aged Vessel in the intermediate temperature range. Samples from the second DOT belonged to a 2016 construction project where they were expected to meet AASHTO M320 specifications for PG 64-22 and 58-22 but failed in the acceptance testing. The DART was used to characterize these binders and was found to favorably detect deviation in fingerprints for compliance. For the tests of materials from asphalt binder supplier location, the samples contained different blends of flux and base material (PG64-22) that the plant combines to produce dual certified (58-22/58-28) samples. The tested samples had five different viscosity levels; one corresponding to the specification, two viscosity levels above it, and two below it. Material-specific fingerprinting showed the expected trends in viscosity but less significant trends in stiffness, which might be specific to this sample. These tests validated that the DART technology has great potential for use in QA, especially for a DOT's verification testing at a higher sampling rate than the current practice. Since the DART technology was found to be promising for use in binder QA, plans for implementation were developed.

INTRODUCTION TO IDEA PRODUCT CONCEPT AND APPLICATION

CURRENT SPECIFICATIONS FOR ASPHALT BINDERS AND NEED FOR A RAPID TESTING DEVICE

Asphalt binders are the cementing agent in hot mix asphalt (HMA) used for paving applications. The asphalt binder makes up a relatively small volume of the HMA but is the most expensive component of the mix design. It is an engineered material and has an impact on the overall HMA behavior and in-situ performance of the pavement. The AASHTO M320 Performance Grade (PG) specification provides guidance for binder PG classification and verification to ensure its performance at different temperatures and aging conditions. Grading designations are related to the average seven-day maximum and minimum pavement design temperatures. The AASHTO M320 specification covers several rheology parameters measured over a range of temperatures and binder aging conditions an asphalt binder is expected to experience in-service. Figure 2 presents a summary overview of the M320 testing regime.

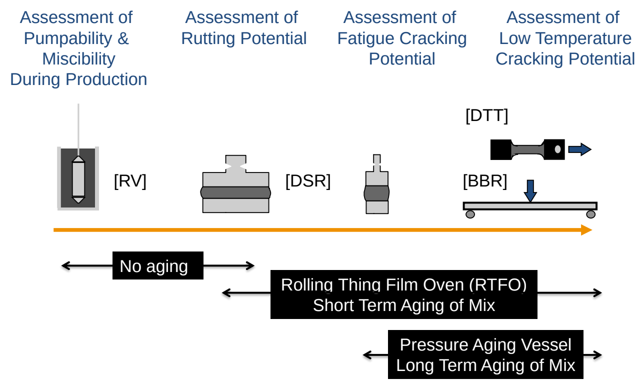


Figure 2. Testing required for the AASHTO M320 PG binder specification.

Multiple standardized laboratory equipment including the Rotational Viscometer (RV), the Dynamic Shear Rheometer (DSR), the Bending Beam Rheometer (BBR), the Direct Tension Tester (DTT) device and specialized aging ovens and temperature control chambers are used to assess the binder properties at the various test conditions. Key parameters tested include the viscosity, η (determined using the RV), the dynamic shear modulus, G*, and phase angle, δ (determined using the DSR), creep stiffness as a function of time S(t) and its slope m (determined using the BBR), and strain at failure (determined using the DTT). Testing is performed on the unaged asphalt, as well as on material aged in the Rolling Thin-Film Oven (RTFO) and Pressure Aging Vessel (PAV) that simulate short term and long-term aging of the binder for physical property testing. A summary of key testing required for PG classification and verification is presented in Table 1.

Table 1. AASHTO M320 Specification Testing for Binder PG Classification and Verification

Binder Type	Classification Testing	Verification Testing
Unaged Binder	Flash Point, Rotational Viscosity, DSR at 2 temperatures	Flash Point, Rotational Viscosity, DSR
RTFO	DSR at 2 temperatures	Mass loss, DSR
PAV	DSR at 2 temperatures, BBR at 2 temperatures	DSR, BBR

It takes approximately 2 days in a certified laboratory for an asphalt binder sample to undergo the entire battery of tests for specification compliance testing. Decidedly, it is not conducive for the entire AASHTO M320 test regime to be used either for quality control (QC) or agency verification on a continuous sampling basis. For this reason, most current state DOT quality assurance (QA) programs are based on the AASHTO procedure PP26 which aims to expedite construction by pre-certifying suppliers if they meet their responsibilities towards assuring PG grade specification compliance. Supplier-side specification testing is done, however, using AASHTO M320; but their QC is typically performed using surrogate devices such as inline viscometers to overcome the time and labor-intensive nature of the AASHTO M320 testing.

When testing for compliance verification, many contractor QC programs, as well as owner agency verification programs, do not include the full battery of tests required by AASHTO M320. Because of the complexity, cost, and resource-intensive nature of the testing involved with the PG binder, they have adopted a simpler testing regimen consisting of testing for either viscosity using the RV or the DSR-high temperature testing of supplier sourced samples. Most agencies have protocols to collect a sample from the production site for each day of paving and then select a very small sample size to perform verification testing. Because the testing is typically performed in a centralized laboratory, agencies often test the material several weeks or months after paving and trafficking the roadway. Some agencies with limited field laboratory capabilities do not perform any testing. The risks associated with accepting asphalt binders delivered to the job site based on supplier pre-certification or limited to no testing are large and unacceptable; this could lead to premature pavement failures as noted by Texas DOT (2003). This risk is multiplied several times when recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), and warm mix asphalt (WMA) additives are added to the virgin mixtures at the construction plant—a common and accepted practice in the industry today with unquantified/unknown consequences on the potential of the additives to alter the intended asphalt binder grade.

The industry has long recognized the problems associated with the lack of rapid binder testing options as well as the challenges for skilled labor and sophisticated laboratory equipment, which are not always available at a job site. The immediate need for a quick test that can serve as an alternative to the AASHTO M320 testing to flag materials out of specification cannot be understated. The DART was developed to address this need.

THE PROPOSED SOLUTION – FUNDAMENTAL CONCEPTS AND STAGES OF DEVELOPMENT

Fundamental Concept of the Technology Proposed

In an attempt to address the QC and verification challenges faced by the industry with respect to asphalt binders, Mallela (2013), Mallela and Carpenter (2000), and Carpenter and Mallela (1996) developed the Duomorph Asphalt Rheology Tester (DART) system at the University of Illinois at Urbana-Champaign under NCHRP IDEA funding. This effort involved a proof of concept study that laid the foundation for future prototype development. The key components of the DART system are:

1. A circular piezoelectric bending duomorph gauge comprising of a stainless steel disc sandwiched between two other concentrically placed lead zirconate titanate (PZT) piezoceramic discs. The gauge can provide a response in air or in the asphalt binder medium. This gauge is immersed in binder liquid to measure its response in the material.
2. An electronic subsystem to (a) electrically activate the duomorph assembly, (b) measure the resulting gauge responses, and (c) store the response for further processing.
3. Software to control gauge activation and data processing to provide the desired outputs.
4. A finite element analyses-based data reduction algorithm to correlate measured data to material properties indicative of in-situ performance.

The piezoceramic layers of the DART duomorph gauge function as electromechanical transducers capable of producing an electrical voltage when a mechanical deformation is applied to them and vice versa. When a voltage is applied to a PZT crystal, it deforms, i.e., expands or contracts. In an electrically asymmetric duomorph gauge (such as the one used in the DART and shown in Figure 3), the poling axes of the two piezoceramic layers are oriented such that when voltage is applied across their electroded faces, one of the layers expands while the other contracts.

In such “parallel type” duomorphs, the electroded piezoelectric faces are driven simultaneously with a voltage of like polarity with respect to an electrical “ground” contact established with the stainless steel shim. This produces a bending action as indicated in the section view of the gauge shown in Figure 3. The resulting maximum bending strain response is measured with the help of strain gauges affixed to the duomorph as shown in Figure 4.

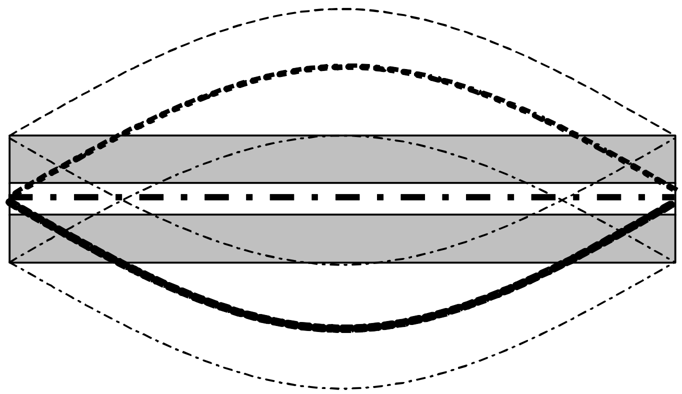


Figure 3. The duomorph in operation (Mallela and Carpenter, 1996, 2000, 2013).

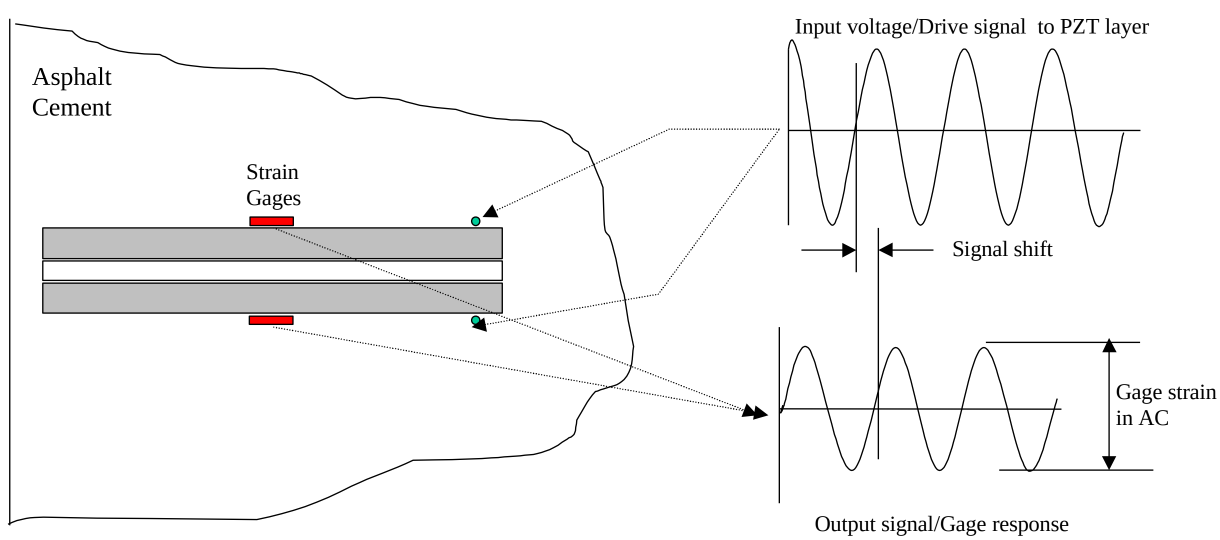


Figure 4. Schematic of duomorph operation illustrating gauge strain and signal shift determination (Mallela and Carpenter, 1996, 2000, 2013).

The magnitude of the bending strain measured at the gauge center is directly proportional to the driving voltage. If the applied voltage signal is sinusoidal, such as in an alternating current (AC) voltage signal, the sensor vibrates sinusoidally at the same frequency as that of the input signal. When the duomorph gauge is operated in air, the strain signal should exactly follow the trace of the driving voltage, i.e., the time lag or “signal shift” is zero. This provides a calibration point for analysis when the gauge is embedded in asphalt. However, when the gauge is embedded in a viscoelastic asphalt binder medium and vibrated, two significant changes occur to the signal. First, there will be a time lag induced in the response of the gauge with respect to the applied driving voltage signal. Second, the peak strain will be reduced due to the confining effect of the stiffness of the surrounding medium. The signal shift, along with the ratio of peak duomorph gauge strains in air and in the medium (i.e., raw gauge responses), provides a means to compute the properties of interest of the surrounding medium. For asphalt materials, the properties of interest are G* and δ of the viscoelastic medium (i.e., the DSR properties from Figure 2).

Original DART Development under IDEA Funding

The IDEA project team (Mallela and Carpenter at the University of Illinois at Urbana-Champaign) performed extensive experimental work in the laboratory and analytical modeling of the DART gauge operating in unconstrained (in air) as well as in embedded environments. Their work concluded that both the raw gauge responses—strain output and phase shift—as well as processed outputs—G* and δ—are sensitive to the properties of the surrounding medium and can potentially be used to rapidly "fingerprint" asphalts during production to identify quality issues. Their work advanced the argument that the DART can be used in rapid QC and verification testing of asphalt binders.

At this stage it was envisioned that the DART can be used as a QC device for two purposes:

1. Consistency check—The most important advantage to be derived by the industry from the implementation of the DART device is the ability to test the consistency of the binder material from the supplier source to the field regularly along the supply chain during a paving project. The ability to perform quick tests (less than 10 minutes) will also allow larger number of test samples and tighter quality checks, which can be of great value for major projects. It will, however, be necessary to develop an original fingerprint of the binder material at the supplier source.
2. Specification Compliance—The key differentiator of the DART system over prevailing methods for binder quality assessment is that it offers a *quick indication* of the specification compliance (*G** and δ parameters) of asphalt binders *in situ* and over a wider range of the asphalt stiffness values. This can be of great value for district laboratories where the AASHTO M320 test apparatus may not be available. It can also be useful at binder supplier locations and terminals for use as a process control tool.

The laboratory prototype was assembled using "bulky" laboratory scale equipment and a desktop computer for data acquisition and data processing. This assembly was not field portable, but it served as a proof of concept of the underlying physics and the success in using it for binder material characterization. Mallela (2013) also identified additional research needs before applying the laboratory prototype of the DART system for field QC and verification applications.

Development of Advanced Breadboard Prototype Under NSF SBIR Funding

Under a National Science Foundation (NSF) grant to Rao Research and Consulting, LLC (RRC) titled *Low-cost Piezoelectric Sensor for Quality Assurance of Asphalt Binders used in Highway Construction (*Rao, et al., 2015) an advanced breadboard prototype of the DART device was developed. This advanced but miniaturized version of the DART was suitable for wider testing and field evaluations.

This breadboard prototype was an effort to miniaturize the DART and make it amenable for field operations. It included improved gauge data reduction software particularly as it related to signal filtering and data processing. Under this effort, limited, but comprehensive, research laboratory trials were performed on three reference asphalt binders that represent a broad range of asphalt binder stiffnesses to establish the methodology and protocol to fingerprint asphalt binders and to verify non-compliance metrics. Significant testing was performed under this effort and statistical criteria were established for using the device in potential QA applications.

Protocols Developed for Fingerprinting and Binder Consistency Check

There exists a minimum requirement for the sample size. The gauge needs to be fully embedded in the binder liquid with approximately one inch of liquid surrounding the gauge. Therefore, for a one-inch diameter piezo gauge, the sample should be tested in a container with minimum dimensions of three inches. It is critical to ensure the gauge is centered in the sample and immersed normal to the liquid surface. Standard quart, pint, and half-pint containers may be used.

There are two steps in the procedure for determining binder consistency along its supply chain or for verifying the compliance of the binder at a field production facility. In the first step, a fingerprint is established for the certified or reference binder based on two outputs from the gauge, the *strain ratio* and *phase shift*. The fingerprint for a certified binder can be established prior to the construction activity, for example, during material certification or during material approval. In the second step, a consistency check or compliance verification of a binder is performed during production by comparing the fingerprint of the field binder with that of the certified material. The methodology can be reviewed as follows:

I. Fingerprinting Certified Binder—*Before Field Use*:
   i. Measure DART response in air at set frequencies of 0–100 Hz (which takes approximately one minute).
      a. Compute peak-to-peak strain (an indicator of elastic behavior).
      b. Measure lag between drive signal and strain signal (an indicator of viscoelastic behavior).
   ii. Measure DART response in a certified binder sample at different temperatures at set frequencies.
      a. Take measurements at specific frequencies and temperatures ranging from 150°F to 70°F in 5°F decrements as the material cools (it takes approximately one minute at every temperature to obtain the frequency sweep measurements).
   iii. Establish unique fingerprint for certified binder sample.
      a. Fingerprint uses DART response in certified binder relative to that in air for each temperature-frequency reading (both the strain ratio and phase lag are used for this purpose).

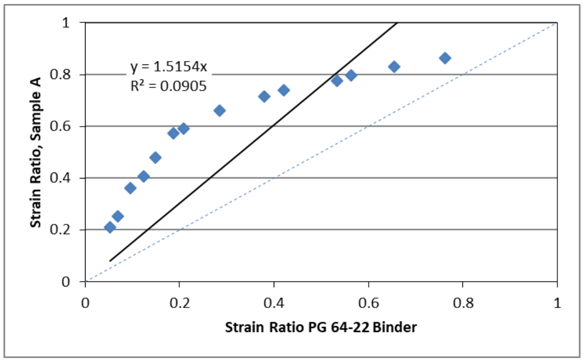
II. Binder Consistency Check OR Grade Verification – *<u>In Field</u>*:
   i. Generate fingerprint for field sample using procedures in steps (i) through (iii) above
   ii. Compare fingerprint of field binder with pre-established fingerprint of certified binder based on statistical parameters.

Note that the time taken to cool the sample in steps I.ii and II.i above depends on the cooling method utilized and the size of the sample. Sample tests have been performed in quart cans, pint cans, and half pint cans. Two extreme methods of cooling have been adopted so far. The time required to cool has been six hours for air cooling a quart-size sample and two hours for cooling pint and half-pint size samples in a temperature bath. It takes approximately six hours to air cool the sample, i.e., leaving the sample exposed to ambient conditions and allowing the sample to cool naturally. The second method of cooling, which was evaluated in the IDEA Type 2 study, provided the necessary temperature drop in a span of 2.5 hours for a pint or half-pint size sample. The standardization protocol will recommend the use of a temperature bath as a preferred means to provide temperature control if testing is time critical.

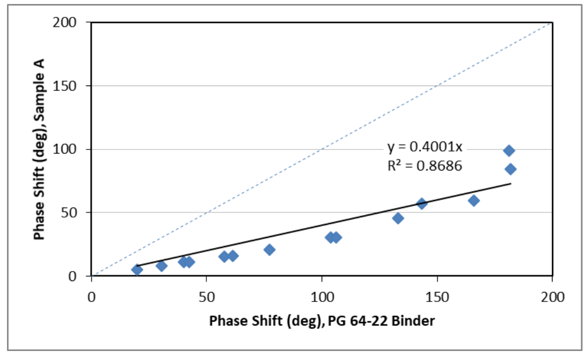
Validation of the Breadboard Prototype

Validations performed under the NSF study showed that the DART was capable of clearly identifying dissimilarity in fingerprints of PG 58-28, 64-22, and 70-22 binders. These samples were selected because they represent the most widely used grades in the Midwestern United States, specifically in Illinois, where they performed this study.

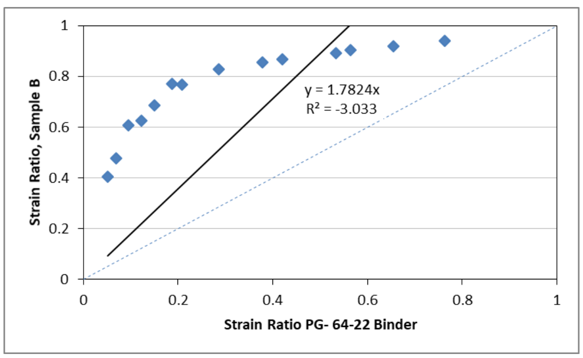
Further, a blind sample study was conducted to evaluate the effectiveness of the device for potential consistency check. Suncor Energy provided 2 reference binder samples with known grading, an unmodified binder, PG 64-22 and a modified binder, PG 64-34. The remainder of the samples were labeled A through H and were blind samples, i.e., the PG gradings for these samples were unknown. The blind samples A, B, C, F, G, and H included a wide range of binder types including PG 58-34, PG46-40, PG64-34, PG58-28, PG76-28, PG64-22. (Note blind samples referenced D and E were cutbacks and their data were not evaluated). All the binder samples were fingerprinted with the DART breadboard prototype and the fingerprints of the reference binders were matched with each blind sample to establish the closest match. This exercise was performed as a test of the DART's effectiveness to perform QC or consistency/uniformity control testing. The device was capable of correctly matching the PG64-22 reference binder with sample H, which was indeed a split sample of the reference PG64-22 binder. Also, the PG 64-34 reference binder was found to match the Sample C (which was a split sample of the PG 64-34 reference binder) as well as Sample A (PG 58-34). The results of the identification of PG 64-22 are presented in Figure 5, which shows a series of comparisons of the strain ratio and phase shift parameter of the PG64-22 binder against all blind samples. Sample H is correctly identified as the matching sample. Further discussions of statistical validations are not presented in this report; however, the validations were statistically rigorous examining the slope, R^2, and comparison of sample means for the correlations between datasets of the samples in each plot of Figure 6.



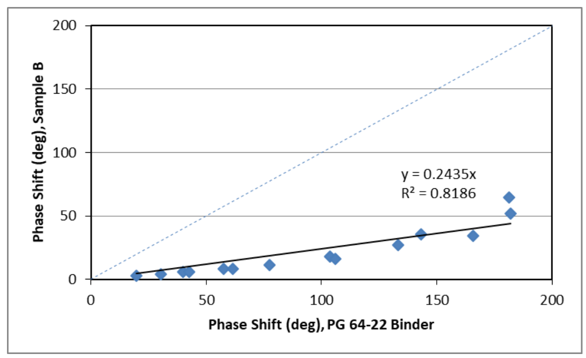
Sample A vs. PG 64-22 strain ratio



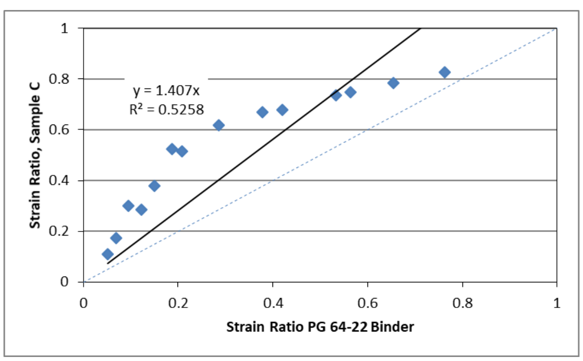
Sample A vs. PG 64-22 phase shift



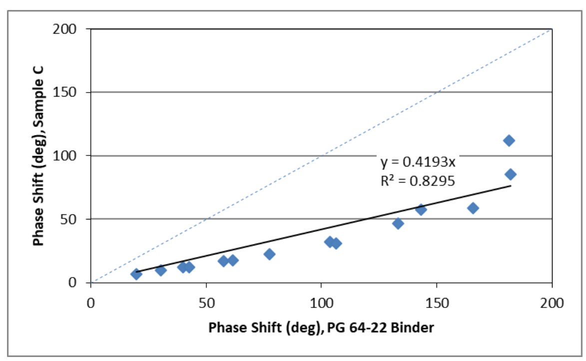
Sample B vs. PG 64-22 strain ratio



Sample B vs. PG 64-22 phase shift

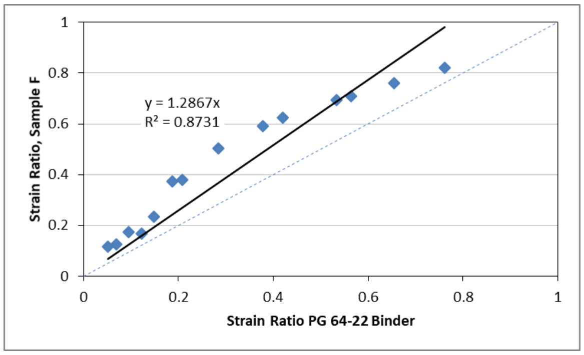


Sample C vs. PG 64-22 strain ratio

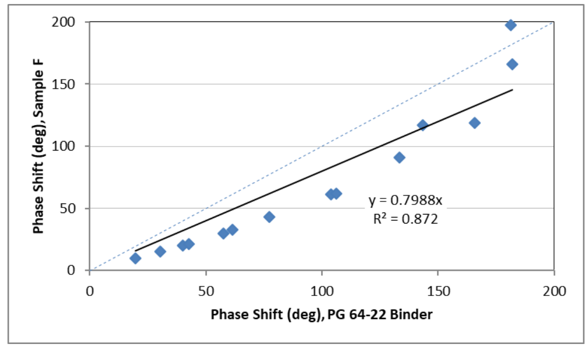


Sample C vs. PG 64-22 phase shift

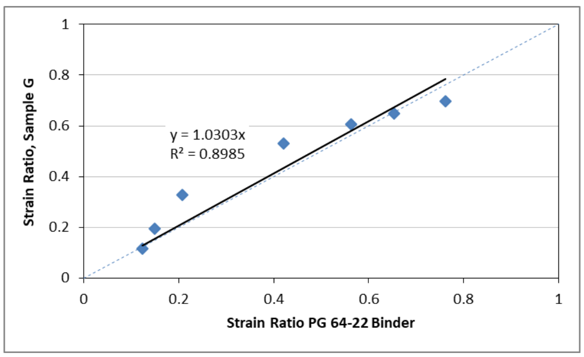
Figure 5. Fingerprint matching Samples A-C and F-H with PG 64-22 reference based on strain ratio (left) and phase shift (right)



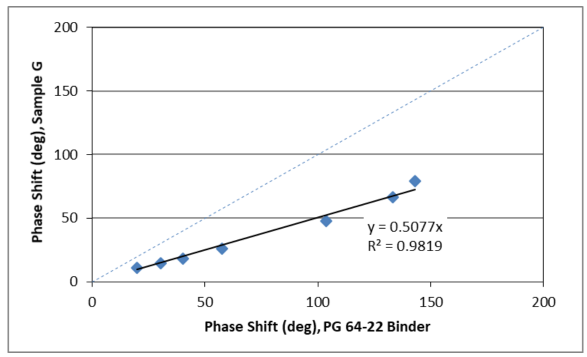
Sample F vs. PG 64-22 strain ratio



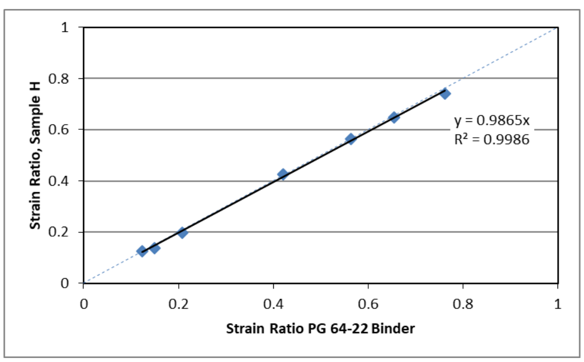
Sample F vs. PG 64-22 phase shift



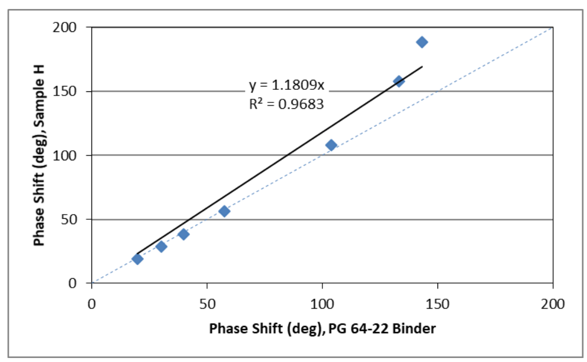
Sample G vs. PG 64-22 strain ratio



Sample G vs. PG 64-22 phase shift



Sample H vs. PG 64-22 strain ratio



Sample H vs. PG 64-22 phase shift

Figure 5. Fingerprint matching Samples A-C and F-H with PG 64-22 reference, cont.

Need for Field Validation

A key outcome of the NSF study was the development of the miniaturized DART device capable of testing asphalt binders in a rapid manner. Under a research-grade and controlled testing environment, the DART's applicability for use in consistency check of binders was confirmed. Therefore, the study demonstrated that the device had potential for use by suppliers in process control during the production of asphalt binders, by contractors to check asphalt grade uniformity as materials are being charged and discharged from tanks, and by owners to verify that the product being delivered to the paving job is what they paid for. However, the DART needed field evaluations before it could be introduced as an effective QC tool for routine use in the paving industry. The two aspects of field validations needed most immediately were:

1. Rigorous and robust field/plant testing to establish validity of the procedure to support wider

implementation in QC.
2. Identification of an acceptable shift from the original fingerprint to ascertain specification compliance under field conditions. Data from the validation testing will be necessary to re-establish the acceptable shift levels.

The IDEA Type 2 Project, NCHRP-193, *DART Field Validation and Prototype Refinement*, bridged the gap between research and implementation. This study mainly involved the “ruggedization” of the device and validation of the procedure to support wider implementation.

Objectives and Accomplishments of the IDEA Type 2 Study

After the successful development of a functional miniaturized DART device, the current IDEA Type 2 project, was conducted to address the specific need of field validation. This project evaluated the DART technology to monitor the consistency and uniformity of asphalt binders in a real-world production environment beyond controlled research grade settings. This included samples from QA laboratories in State DOT Central or District facilities as well as samples from binder supplier facilities. This study involved the demonstration and verification of the benefits of using an increased sample size for consistency and compliance verification. Such testing is relevant for a State DOT field laboratory, a contractor QC lab, or an asphalt binder production facility. The validation was going to be most meaningful if the DART could identify samples that did not meet specifications. These experiments were essentially simulating the use of the DART for flagging defective materials in a plant.

First, the team focused on ruggedizing the device for field operations, making physical improvements for field portability and software improvements to enhance automation and reduce user controls. Significant improvements to the standard protocols and to the electronic subsystem in the device (specifically the introduction of a potentiometer in the circuit to enable balancing the bridge for each sensor) to reduce signal drift. A large set of AC binders, including samples from three suppliers, was tested in the team’s laboratory facility. In general, the DART device was capable of matching like materials (i.e., the same performance grades) and distinguishing samples of different grades. The team also coordinated with State DOTs and an asphalt binder supplier for testing samples consistent with an experimental design necessary to validate the DART for field applications.

INVESTIGATION AND VALIDATION

This section summarizes the primary results obtained from the testing and validation of the DART. Tests were conducted at three levels to validate the following abilities:

1. Matching binders of the same performance grade and distinguishing between different performance grades to validate the fingerprinting and binder consistency check methods established previously.
2. Identifying binders from construction projects that failed standard AASHTO M320 verification testing to simulate field application of the DART and test at a production site where increased sampling is possible because of the simplicity and efficiency of the DART.
3. Tracking viscosity changes in a binder at a producer's location to simulate blending and modifications constantly made in a producer location and where binder consistency checks can be time critical during the high-demand construction season. The ability to obtain a preliminary check on specification compliance (as process control) can add efficiency to the processes in the producer's plant.

This section presents results from all three categories of testing.

TESTING TO MATCH PG GRADED BINDER SAMPLES

The project team used samples from three sources:

1. Binders used in Illinois (IL) on Illinois DOT projects and provided by the Illinois Center for Transportation (ICT) at the University of Illinois at Urbana-Champaign. ICT provided research laboratory grade test results for AASHTO specification testing of binders used in Illinois for DART evaluations.
2. Binders supplied by asphalt mix supplier Emulsicoat, Inc., in Urbana, IL.
3. Binders supplied by the *Suncor Energy* refinery from Colorado.

Matching Same Grade Binders

Fingerprints were developed for several samples and were compared based on statistical criteria developed for the DART, which examines the slope and R^2 of the strain ratio comparisons and the slope of the phase shift comparisons. This section presents the results from select binder matching analyses. Comparisons of PG 64-22 binders from Suncor and IL, PG 58-28 binders from Suncor and IL, PG 58-28 binders from IL and Emulsicoat, and PG 70-22 binders from IL and Emulsicoat are presented in Figure 6 through Figure 9 respectively. These figures show data plotted, a linear trendline with the correlation statistics reported, as well as the line of equality to visually illustrate the quality of fit.

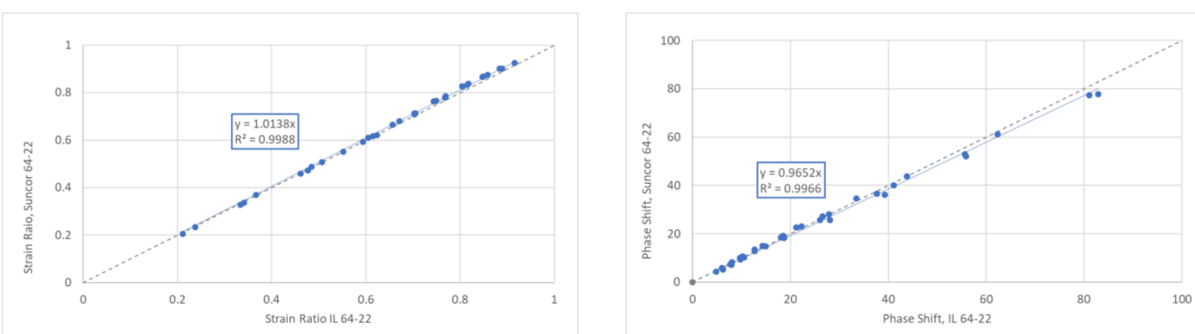


Figure 6. Fingerprint matching based on strain ratio (left) and phase shift (right) for PG 64-22 samples from Suncor and IL

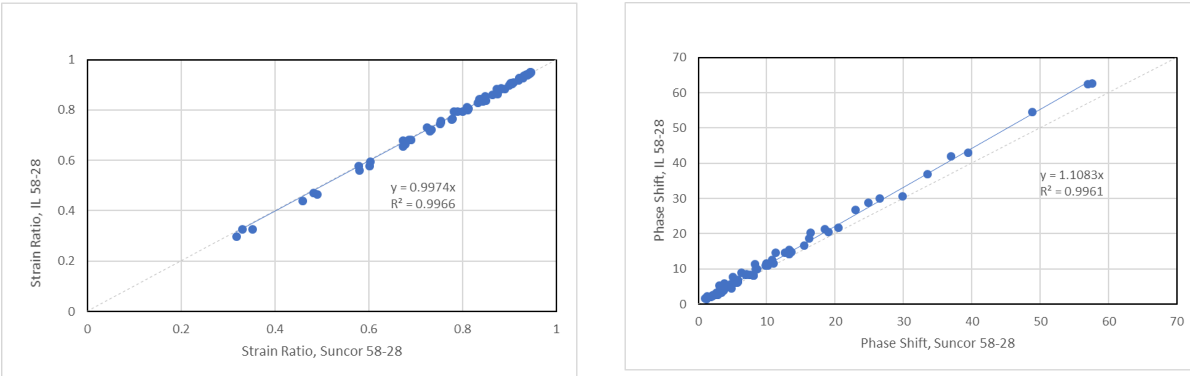


Figure 7. Fingerprint matching based on strain ratio (left) and phase shift (right) for PG 58-28 samples from Suncor and IL

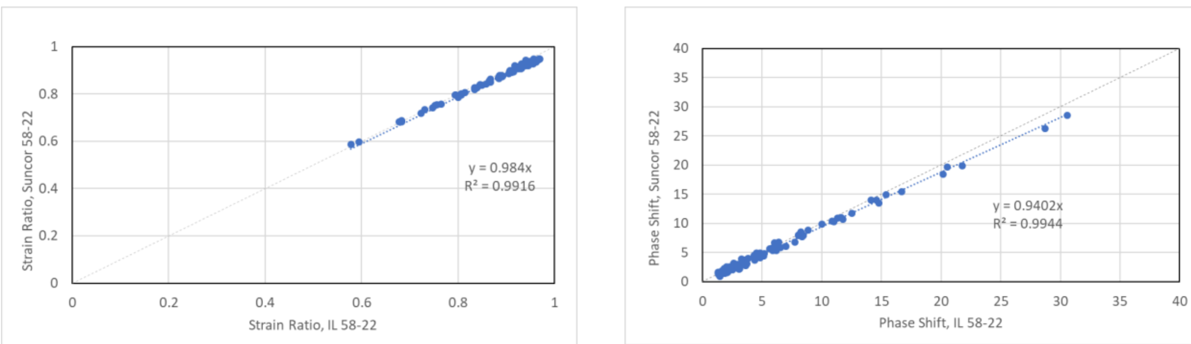


Figure 8. Fingerprint matching based on strain ratio (left) and phase shift (right)for PG 58-28 samples from Suncor and Emulsicoat

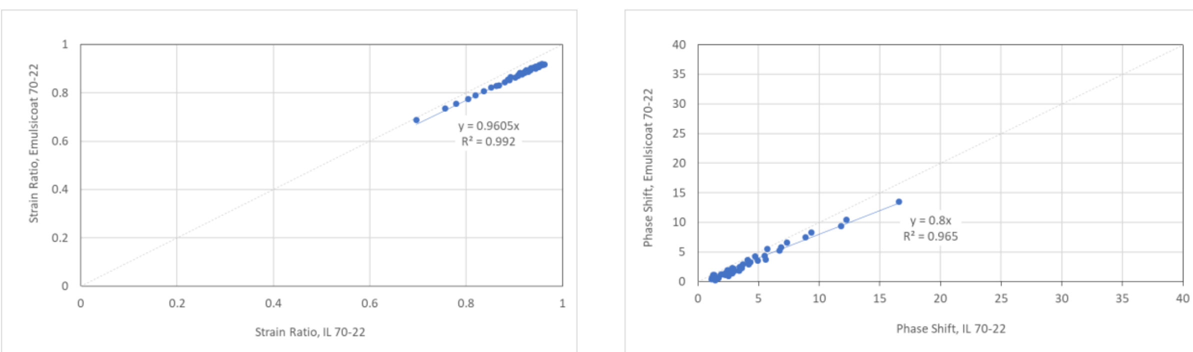


Figure 9. Fingerprint matching based on strain ratio (left) and phase shift (right) for PG 70-22 samples from Emulsicoat and IL

It is worth noting that data used for comparisons in these plots were essentially good quality data obtained in the temperature and frequency sweeps. Data filtering standards to eliminate data with higher than acceptable noise in the signal and strain ratio values were utilized. Note that these data filtering standards were uniformly applied across all validations of the DART (and were not adjusted for each comparison or each sample). Also, data sets used in the comparisons belonged to temperature and frequency ranges that were found to be relevant for specific binder types. All comparisons made, four of which are presented here, validated the ability of the DART device to identify and match binders of the same performance grade drawn from different sources. The PG 70-22 samples in Figure 9 showed a slightly less than ideal match with regard to the slope of the correlation in phase shift. Future testing with additional samples from other sources might help resolve this. Also, the true grades of the samples were not verified, which could be helpful with further investigating the reason for the discrepancy.

Distinguishing Between Dissimilarly Graded Binders

Fingerprints for binders of different grades were compared to validate the effectiveness of the device to identify binder non-compliance. The fundamental requirement was to be able to distinguish binders of different performance grades. While this was amply demonstrated under previous studies (see Figure 5), several comparisons were made under the IDEA project. Figure 10 displays the results of the correlation of data for Suncor PG 58-28 vs. PG 64-22, and Figure 11 displays the results for Illinois PG 64-22 vs. PG 70-22. Note the deviation of the slope from the value of 1.0 for all the plots. The strain ratios and phase shifts also show clear trends; the stiffer the binder, the lower the strain ratio and larger the phase shift. These results clearly demonstrate the ability of the device to distinguish between binders of different stiffness and viscosity (i.e. different performance grades) based on the same statistical parameters that were used to match binders of the same grade.

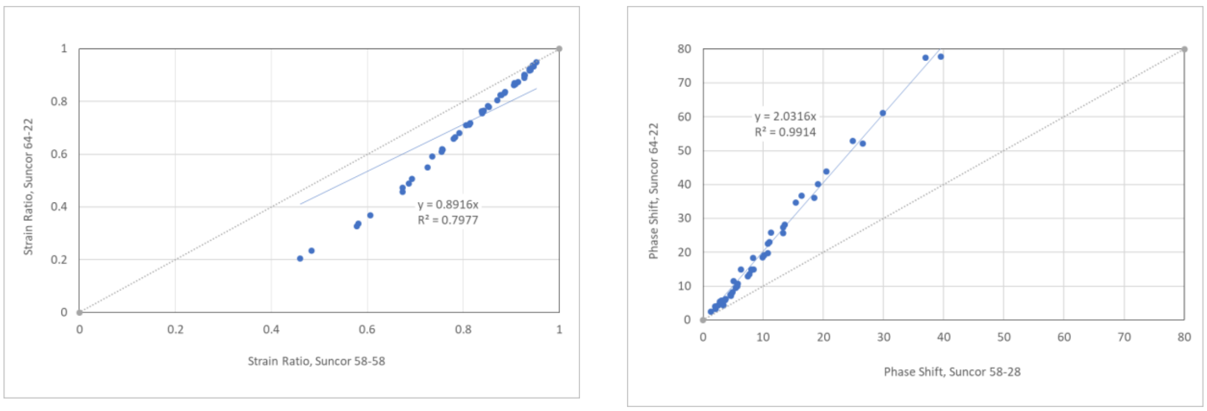


Figure 10. Fingerprint to distinguish PG 58-28 and PG 64-22 samples from Suncor based on strain ratio (left) and phase shift (right)

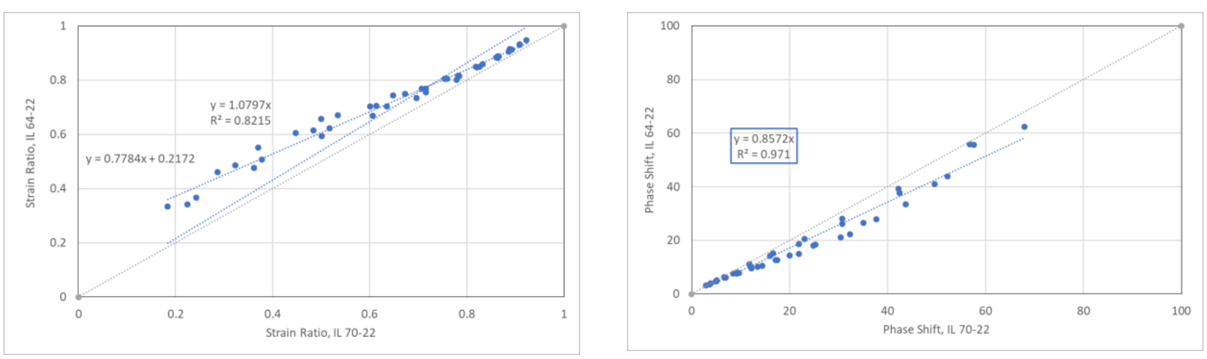


Figure 11. Fingerprint to distinguish PG 64-22 and PG 70-22 samples from IL based on strain ratio (left) and phase shift (right)

Summary

The validations of the DART device discussed in this section and presented in Figure 6 through Figure 11 demonstrate its ability to perform binder consistency checks. Thus, the device is considered effective for use in QA to reliably verify binder grade. The DART has potential for use in contractor testing labs and production plants or field laboratories where owner agency verifications are conducted. Because the device is simple to use, is portable, and can offer quick test results, it is possible to perform verification testing at a higher sampling rate, which may include testing on a daily basis when the samples are collected instead of testing one random sample from multiple days of paving. The motivation is in the ability of the owner to discover non-compliant samples because of the increased sampling rate and avoid costly errors discovered several years after construction is complete. The next step in the validation procedures was to demonstrate that field samples from construction projects that were found to be non-compliant could be flagged by the DART based on fingerprints of the field samples and certified samples.

TESTING TO VALIDATE DART FOR FIELD QA

Under this segment of DART validation testing, samples from field construction projects in 2016 from 2 States were used. Samples used in the tests included binders that failed the AASHTO specifications.

Samples from State 1

Binder samples were fingerprinted from the QA laboratory of a Southeastern State where two binder grades are primarily used, PG 76-22 and PG 67-22. Certified samples of both binder grades were tested. In addition, a binder sample that failed to meet the specification compliance for PG 67-22 was also tested. AASHTO M320 test results for these samples are summarized in Table 2. The table shows that the reference samples of PG 76-22 and PG 67-22 satisfied all AASHTO M320 specification requirements, while the failed binder did not meet the specification for the PAV-aged DSR testing and the low temperature BBR testing. PAV binder samples simulate long-term asphalt aging, and tests performed with PAV binder samples at intermediate temperatures are indicators of the material’s resistance to long-term fatigue loading and low temperature thermal cracking. PAV sample preparation is also time and labor intensive, requiring 20 hours of pressurized aging treatment to 300 psi and elevated temperature (100°C for this region of the U.S.) followed by two hours of degassing before testing. If DART testing of unaged binders during construction can provide an indicator of the sample’s deviation from the reference binder sample at intermediate and low temperatures, the device can be considered immensely valuable as a QA tool directly providing a measure of performance.

Table 2. AASHTO M320 Specification Testing for Samples Tested in State 1

Test	**Accepted Range**	**Reference PG 67-22**	**Failed PG 67-22**	**Reference PG 76-22**
Unaged Binder				
Viscosity (Pa-S)	<3	0.5	0.6	2
G*/ sin δ delta (kPa)	>1.0	1.13	2.06	2.3
RTFO Binder				
G*/ sin δ (kPa)	>2.2	2.64	4.61	4.23
PAV Temp 100C Binder				
G*(sin δ) (kPa)	<5000	3740	**6180**	1790
BBR Test Results:				
Creep Stiffness, S (Mpa)	<300	215	**322**	177
Slope (m)	>0.3	3.09	**0.28**	0.32

The comparisons of fingerprints of the PG 67-22 and PG 76-22 certified samples from State 1 are presented in Figure 12. Figure 12 also shows the results of a retest of the PG 76-22 sample. Based on the pre-established statistical criteria, the DART fingerprint comparisons clearly match the PG 76-22 sample data against its retest data and indicate the mismatch of the PG 76-22 vs PG 67-22 sample data. This validation clearly demonstrates the applicability of the DART device in field operations to ensure the right binder type is being used in the paving operation.

Further, Figure 13 shows a comparison of fingerprints of a certified PG 67-22 and a failed PG 67-22 sample. The results clearly indicate that the DART distinguishes between these samples. The specification test results in Table 2 indicate the failed sample is stiffer than the certified binder as corroborated by the test data in Figure 13. These data offer significant evidence of the ability of the DART to identify noncompliant materials and support the potential for using the DART in field laboratories or at HMA production plants where samples may be tested on a routine basis.

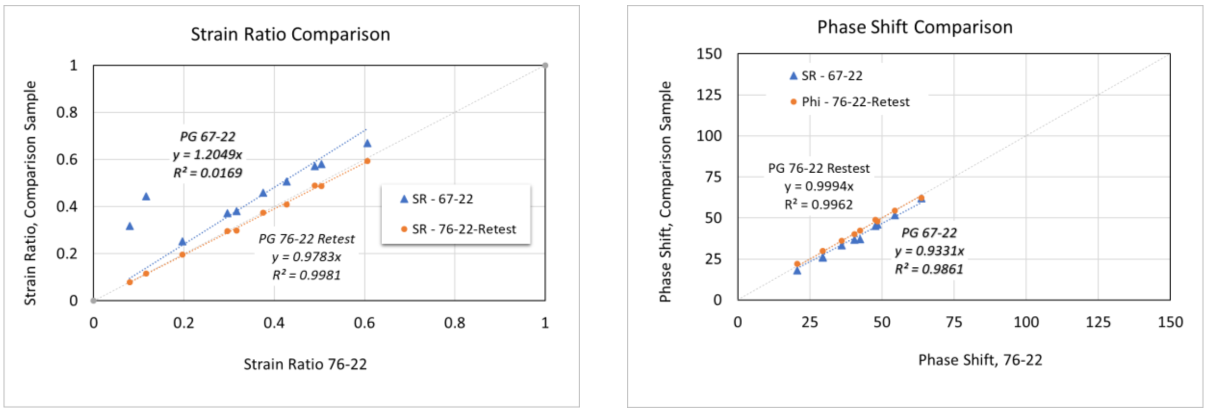


Figure 12. Fingerprint comparisons to distinguish PG 76-22 and PG 67-22 samples from State 1 based on strain ratio (left) and phase shift (right)

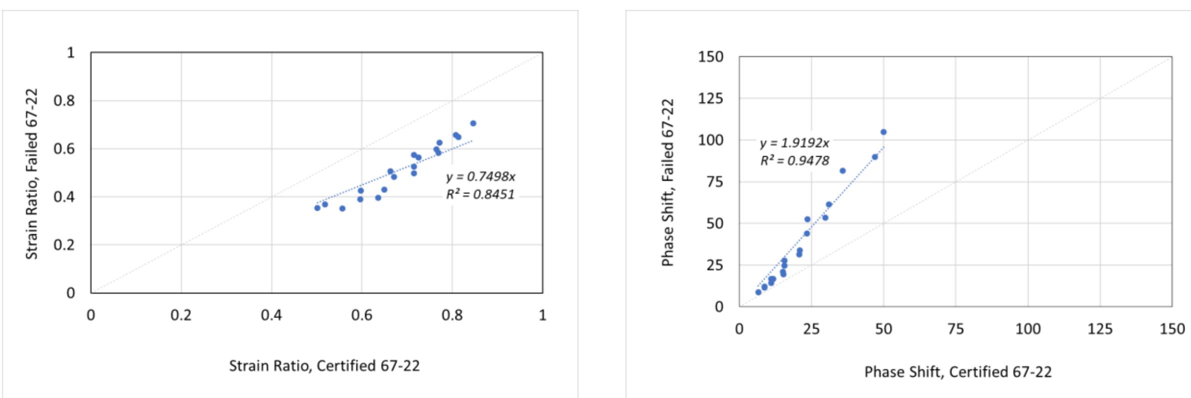


Figure 13. Fingerprint comparisons to identify a non-compliant 67-22 binder sample from State 1 based on strain ratio (left) and phase shift (right)

Samples from State 2

Samples from a State in the Midwestern region of the U.S. included binders that failed to meet the AASHTO M320 specification for PG 58-22 and PG 64-22 in two separate 2016 construction projects. Table 3 presents DSR test results for the QA verification samples of the unaged binder provided by the State DOT. The project team obtained samples from field testing to evaluate the DART. However, samples representing the certified and approved binder were not available at the State DOT for direct comparisons of fingerprints generated with the DART.

Table 3. DSR Test Results for Unaged Binder Samples from State 2

PG 58-22 Binder		PG 64-22 Binder	
Sample Paving Date	**G*/ sin δ delta (kPa)**	**Sample Paving Date**	**G*/ sin δ delta (kPa)**
04/04/2016	0.87	5/31/2016	0.96
04/05/2016	1.01	6/2/2016	0.96
04/06/2016	0.92	6/7/2016	0.93
04/07//2016	1.25	6/21/2016	0.86

The results for the PG 58-22 binder verification testing indicate that the samples failed the specification requirement for the unaged binder on two of the paving days, 04/04/2016 and 04/06/2016. The samples that passed the specification requirement were used in lieu of the approved binder for generating fingerprints in this comparison. The comparison of fingerprints of the passing sample from 04/05/2016 and the failed samples from 04/04/2016 and 04/06/2016 are presented in Figure 14. Based on the statistical criteria established for verifying compliance (details of statistical analyses not discussed in this report), the samples on 04/04/2016 and 04/06/2016 deviate from the sample complaint with specifications. Note the poor correlation and/or slope significantly less than 1.0.

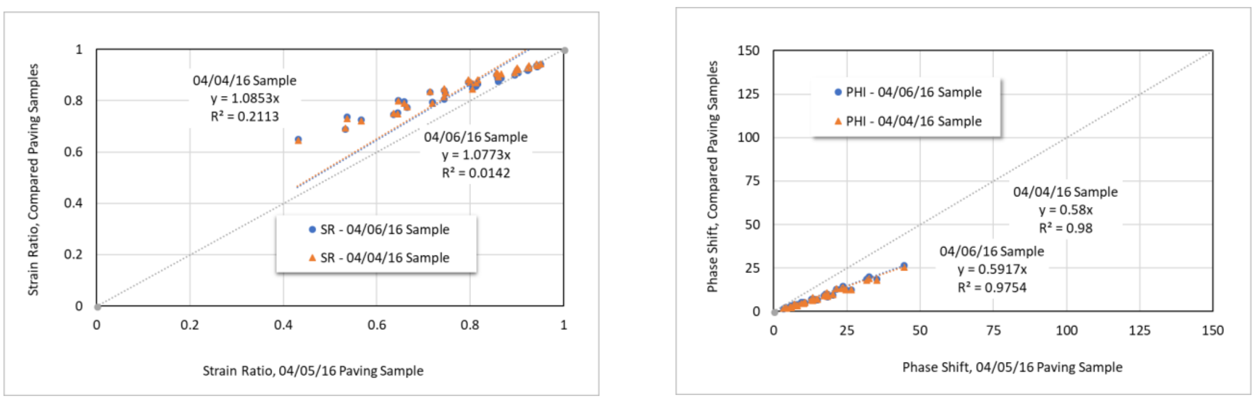


Figure 14. Fingerprint comparisons of 04/05/2016 PG 58-22 sample with samples from 04/04/16 and 04/06/2017 based on strain ratio (left) and phase shift (right).

The results for the 64-22 binder indicate that all samples had G*/ sin δ delta values of less than 1.0; therefore, all samples were considered to have failed. Because the project team did not have access to the certified or the approved binder samples, the verification samples shown in Table 3 were fingerprinted for relative comparisons. The project team compared results of the sample from paving on 6/21/16 against the sample from paving on 5/31/16. Figure 15 presents the results of the fingerprint comparisons for phase shift. Based on their unaged DSR test results, both samples from paving on 6/7/16 and 6/21/16 deviate in their DART response from the paving sample collected on 5/31/2016 and report lower phase shift values. This is noted in Figure 15; the relative DSR test values correspond to the slope of the trend lines in the plots. The DART was therefore successful in identifying a noncompliant sample when sample testing was performed at an increased sampling rate. This indicates the true potential of the device.

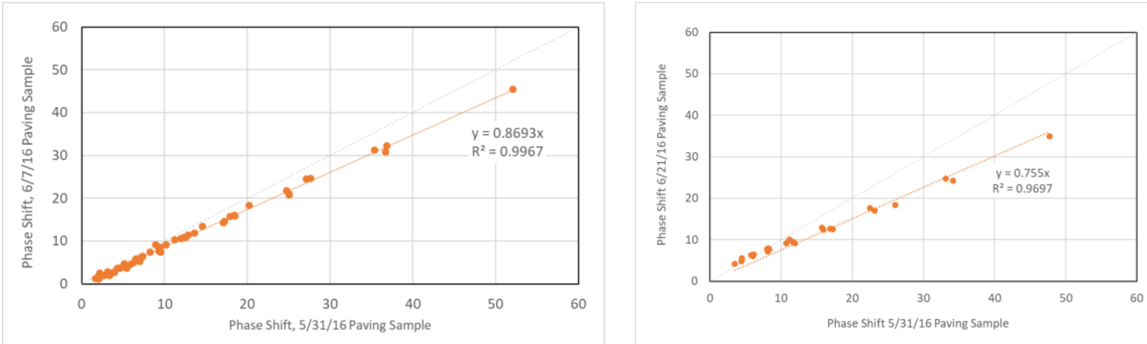


Figure 15. Phase shift fingerprints comparisons for 5/31/2016 paving sample with 6/7/2016 (left) and 6/21/2016 (right) paving samples to identify relative changes.

Summary

Test results of DOT QA laboratories in States 1 and 2 suggest the DART has demonstrated its potential for application in field laboratories. These results clearly validate that if used on samples collected more frequently, the DART improves the ability to detect binder non-compliance, which has hitherto not been an option because of long testing times and the inability to test at field laboratories.

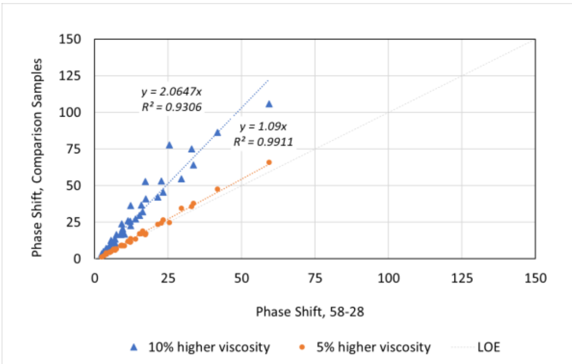
TESTING TO DEMONSTRATE USE OF DART AT BINDER PRODUCER FACILITY

This study demonstrated the application of the DART technology at a binder facility. Although the validation efforts focused mostly on the ability to use the DART to alert the possibility of a noncompliant binder (as discussed in the previous sections), the DART could also have the potential for use in binder producer locations where AASHTO M320 specification tests are required for certification during production. Binder producer facilities blend various proportions of tank asphalt(s) and cutback to produce binders meeting specific PG grade specifications. Alternatively, these operations also involve optimizing the addition of polymers to result in products meeting AASHTO M320 requirements. Often these operations, especially blending operations, utilize results from simple tests, such as viscosity or penetration tests, as a surrogate test to target optimum blending proportions. Even if the optimization is based from a simple test, such as viscosity, the material produced has to satisfy AASHTO M320 performance requirements that are not directly correlated to viscosity alone. It takes two days of testing to verify AASHTO M320 compliance, and if not satisfied, it consumes additional time to iterate the blending process until the specifications can be met. The DART could have a potential application in such facilities to estimate blending proportions based on mechanical properties at multiple temperature-frequency combinations.

For example, a plant in the Midwest performs blending to produce a PG 58-28 and PG 58-22 dual-certified material. The operations involve blending of PG 64-22 and flux material based on viscosity testing. The blending may be in the following proportion based on viscosity of the individual components:

- 40–60% blend of flux at viscosity of 270 cP and PG 64-22 at viscosity of 2050 cP
- 25–75% blend of flux at viscosity of 135 cP and PG 64-22 at viscosity of 1800 cP

For the purpose of this study, a given reference PG 58-28 sample was known to be at approximately 925 cP. Additional samples with blends to achieve 5 percent higher, 10 percent higher, and 10 percent lower viscosity were tested. Figure 16 displays the results from DART comparisons for the phase shift parameter, showing the trends expected.



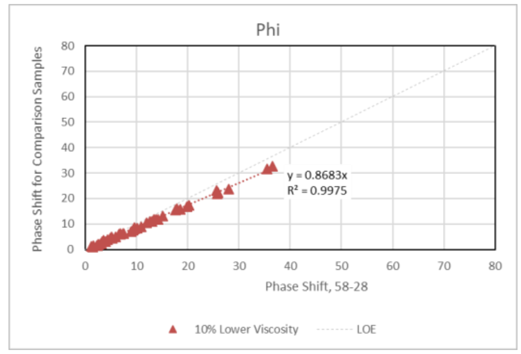


Figure 16. Phase shift fingerprints comparisons for PG 58-28 sample with samples with (left) and 6/21/2016 (right) paving samples to identify relative changes.

It is expected that if implemented for producer facility operations, the DART can be used as a screening device to assist in optimizing blending operations. The optimization will then utilize multiple points across different temperature-frequency combinations to center on a specific fingerprint rather than using just two viscosity readings (that of the flux and tank asphalt) to help zero in on the blending proportions. The use of the DART would provide a more reliable means of meeting the AASHTO M320 specifications because the principle of the DART operation is the mechanical response of the sensor. The project team demonstrated a preliminary evaluation of this potential, but additional testing is required in a producer facility to develop an optimization procedure.

IMPLEMENTATION

BENEFITS AND POTENTIAL PAYOFF FOR IMPLEMENTING THE DART SYSTEM

The demonstration of the working DART prototype validates that this technology is field ready and has immense potential as a QA tool. Based on the previous discussions, the DART system offers the following benefits for the various stakeholders involved:

1. Is simple to use and can rapidly detect deficient quality.
2. Poses less risk of premature pavement failures for owners and the traveling public.
3. Lowers risk of accepting inferior materials for owners.
4. Lowers risk of litigation between suppliers, contractors and owners.
5. Provides cost savings for suppliers and owners resulting from optimized full-scale standard testing using DART as a screening device.
6. Provides data previously unavailable to advance the understanding of binder science.

Table 4 presents a summary of DART features in comparison to existing binder testing technologies. It gives a snapshot of potential benefits of introducing the DART.

Table 4. Features and Capabilities of the DART in Relation to the Current Technologies

Device Features	DART	AASHTO M320 Testing			
		Rotational Viscometer	DSR (High temperature)	DSR (Intermediate temperature)	BBR
Viscosity measurement at high temperature	No	Yes	N/A	N/A	N/A
Rutting potential characterization	Yes	N/A	Yes	N/A	N/A
Fatigue characterization	Yes	N/A	N/A	Yes	N/A
Thermal cracking potential characterization	No	N/A	N/A	Yes	Yes
Rapid testing	Yes	Yes	No	No	No
Fingerprinting for specification compliance	Yes	No	No	No	No
Need for skilled operator	No	No	Yes	Yes	Yes
Portable for field use	Yes	No	No	No	No
Field QC device (practical)	Yes	No	No	No	No
Verification	Yes	No	No	No	No
Acceptance	No	Yes	Yes	Yes	Yes

The development of such a tool is also timely because there is an increasing importance on comprehensive material characterization for pavement performance prediction. The recent development of pavement prediction models—such as those in the AASHTOWare Pavement ME Design and FHWA Performance Related Specifications (PRS) PaveSpec 4.0 and ongoing 5.0—have used binder material properties as key parameters to predict AC layer rutting, thermal, and fatigue properties (AASHTO, 2008). These findings were corroborated in AASHTOWare Pavement ME local calibration and implementation studies, where laboratory test data and model validations demonstrate that the binder type had a significant impact on E* for loading frequencies ranging from 0.1 to 10,000 Hz.

These prediction tools have also created a segue for ongoing FHWA efforts to utilize QA data as a leading indicator of predicting performance of as-built pavements for use in an agency's pavement management system

(PMS). Clearly, the collection of larger QA/QC data samples that provide an indication of the quality, and therefore performance, of the "as-built" is only going to improve performance prediction for each segment (or measurement unit) rather than use an assumed/project-specific value determined from the certification process.

IMPLEMENTATION PLANS

The project team recognizes that the implementation potential is high, and the target uses include sample compliance checks at field and district laboratories, agency verification at HMA production plants, and consistency checks along the supply chain. Based on this assessment, a conservative estimate of five field and district laboratories per State is made. The implementation of such a device will require buy-in from the agency and contractors. The project team recognizes the challenge to overcome institutional barriers and gain acceptance by the industry. The validation and endorsement from agencies may be essential and therefore the project team will seek early adopters in the industry. The project team also recognizes the need for further ruggedization of the device and design modifications if it must be made production ready. Therefore, it is exploring either networking with equipment manufacturers or developing plans for a production-ready device.

SUMMARY AND CONCLUSIONS

SUMMARY

This NCHRP IDEA Type 2 project provided field validation of a prototype for DART, a portable liquid binder testing device that is inexpensive, simple to use, and quick to provide binder consistency check in production plants and field laboratories. The DART is proposed as an effective tool for process control of asphalt binders to enable larger sampling rates and faster testing of asphalt binders. Testing can be completed in as few as 2.5 hours with minimal operator time or skills. The DART can supplement, although not replace, AASHTO M 320 PG specification testing. The AASHTO M320 PG specification covers several rheology parameters measured over a range of temperatures and aging conditions an asphalt binder is expected to experience in-service. It takes approximately two days in a certified laboratory for an asphalt sample to undergo the entire battery of tests for specification compliance testing. Decidedly, it is not conducive for the entire AASHTO M320 test regimen to be used either for quality control (QC) or agency verification on a continuous sampling basis. The DART has the potential to address this need for quick test results in the field.

The current version the field-ready prototype DART has evolved over a series of projects. Previous IDEA research studies established the proof of concept of the technology, and ensuing NSF research developed a miniaturized device. When evaluated under a research-grade, controlled testing environment, the miniaturized DART prototype's success in consistency check of binders was confirmed. Preliminary results were encouraging to consider the DART for use by suppliers in process control during the production of asphalt binders, by contractors to check asphalt grade uniformity as materials are being charged and discharged from tanks, and by owners to verify if the product being delivered to the paving job is what they paid for. However, the DART needed field evaluations before it can be introduced as an effective QC tool for routine use in the paving industry.

The IDEA Type 2 Project, NCHRP-193, *DART Field Validation and Prototype Refinement*, was performed to bridge this gap across research and implementation. This study mainly involved the "ruggedization" of the device to a field prototype (shown in Figure 2) and validation of the procedure using the DART to identify noncompliant binders in field and in a production plant. The study involved the use of samples from construction projects in two State DOTs, one in the Southeast and one in the Midwest. The samples tested included those that failed to meet AASHTO M 320 specification compliance compared with those that satisfied the specification requirements. The DART field prototype was also evaluated as a means to provide process control in an asphalt binder production facility. The key outcome of this research is the demonstration of the validity of the DART technology for use in quality control. These results provide the necessary data evidence for the industry to consider implementation.

CONCLUSIONS

Based on the testing performed under the current Type 2 IDEA study, the following conclusions can be made about the capabilities of the field prototype DART device:

- Matching binders of the same PG grading and distinguishing between different grades—The DART proved to successfully match similar PG binders and distinguish between them even when the materials were from different sources. This was considered a validation of the fingerprinting and binder consistency check methods established previously. The test program involved the verification of matching between two PG 64-22 binders, three PG 58-22 binders, and two PG 70-22 binders. Based on the same fingerprinting methods, the DART distinguished between different binder types as well. These validations are presented in Figure 5 through Figure 11 in the report.
- Identifying binders from construction projects that failed standard AASHTO M320 verification testing—This was a simulation of a field application of the DART for testing at an HMA production site where increased sampling of the binder is possible because of the simplicity and efficiency of the DART. Tests

were performed on samples from State DOT construction projects where binder samples did not meet compliance requirements based on standard AASHTO M 320 testing and the DART was found capable of successfully identifying the lack of compliance.

Samples from State 1, a state in the Southeastern part of the United States, included the two most commonly used binder grades, PG 67-22 and PG 76-22. The DART was able to first distinguish between the two binder types (Figure 12) and then to flag a non-compliant PG 67-22 binder when comparing its fingerprint to that of a certified PG 67-22 sample (Figure 13).

Samples from State 2, a state in the Midwestern region of the Unites States, consisted of field samples that failed to meet PG 58-22 and PG 64-22 requirements. Although results from these binders were not compared against the original certified binder samples, comparison with a passing sample showed the lack of compliance of the failed sample in the case of the PG 58-22 binder (Figure 14). Likewise, relative comparisons between samples from multiple days of paving showed the alteration/changes made to the binder on different days of paving (Figure 15).

- Tracking viscosity changes in a binder at a producer's location—This was a simulation of blending and modifications constantly made in a producer location and where binder consistency checks can be time critical during the high-demand construction seasons. The DART's ability to obtain a preliminary check on specification compliance (as process control) to add efficiency to the processes in the plant was demonstrated (Figure 16). The development of a more systematic procedure to optimize plant blending operations will require more extensive testing and verification. This study provided understanding of the potential for use in such applications.

Implementation

The implementation of the DART device offers several benefits for the various stakeholders involved:

- Simple and quick testing to detect deficient quality.
- Reduced risk of premature pavement failures for owners and the traveling public.
- Lowered risk of accepting inferior materials for owners.
- Lowered risk of litigation between suppliers, contractors, and owners.
- Cost savings for suppliers and owners resulting from optimized full-scale standard testing using DART as a screening device.
- Generation of data previously unavailable to advance the understanding of binder science.

This study did not make any strides with the actual implementation of the device in practice. However, this study provided the much-needed data evidence and device refinements to support field implementation. The results suggest that the implementation potential is high, and the target uses include sample compliance checks at field and district laboratories, agency verification at HMA production plants, and consistency checks along the supply chain. The implementation of the DART device will require buy-in from the agency, contractors, and the industry. The current research provides objective reasons for all stakeholders to move forward with implementation.

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APPENDIX – RESEARCH RESULTS

WHAT NEED DID THE PROJECT ADDRESS?

Asphalt binder is a critical component of the volumetric design of hot mix asphalt (HMA). Asphalt binder properties impact pavement performance. The AASHTO M320 Performance Grade (PG) specification provides guidance for asphalt binder classification and verification to ensure its performance at different temperatures during paving and aging conditions. The specification covers multiple tests to determine the different rheology parameters measured over a range of temperatures as well as binder aging conditions an asphalt binder is expected to experience in-service. It takes approximately two days in a certified laboratory for an asphalt sample to undergo the entire battery of tests for specification compliance testing. Thus, it is not conducive for the AASHTO M320 test regimen to be used either for quality control (QC) or for agency verification on a continuous sampling basis.

Binder properties may change along its journey from its point of production to the paving job site due to various reasons including overheating, tank contamination, steric hardening, or modifications. Current practice relies on binder certification by the producer at the point of origination and acceptance by the owner based on this certification. Limited independent verification is performed by the owner primarily due to the time, cost, skilled labor, and resources necessary for testing. Typically, samples collected during HMA production are sent to the State Department of Transportation (DOT) central lab for verification. The verification tests are performed on a limited number of samples and usually many days after paving. This may result in the inability to detect an incorrect binder during paving. Therefore, owner agencies will have significant benefits if the quality and consistency of asphalt binders can be verified in field laboratories during paving operations to ensure material consistency. The IDEA Type 2 research provides field validations for a binder test device that addresses this need.

WHAT WAS THE GOAL?

The objective of the IDEA Type 2 research was to validate a field prototype of the Duomorph Asphalt Rheology Tester (DART), a portable liquid binder testing device that is inexpensive, simple to use, and quick to check binder consistency in production plants and field laboratories. The DART technology, which has evolved over multiple research projects, was verified under controlled laboratory experiments in the past. This study focused on making the device more rugged for a field prototype (shown in Figure 17) and validating the procedure to use the DART to identify noncompliant binders in the field using samples from real-world construction projects. The research team also used the DART in a production facility to assess its applicability in optimizing binder production operations.

RESEARCH ACCOMPLISHED

Previous studies established a preliminary test protocol to fingerprint binder samples. The procedure involves recording the DART response in the binder sample at temperatures from 150°F to 70°F, and at frequencies from 0.5 to 100 Hz, to generate a material-specific fingerprint. The fingerprint uses the response of the DART in the binder sample relative to its response in air and utilizes data filtered based on preset criteria for signal noise tolerance and physical relevance of the magnitude of response. The fingerprint of a certified binder (or an approved binder) is compared against the fingerprints generated for field samples to determine the consistency of the binder used in the project. A lack of consistency is determined based on statistical parameters established under the DART research studies. This IDEA Type 2 project bridges the gap between research and application by providing the necessary field validation to support agency implementation. This study validated the following:

- Tests involving multiple comparisons of binders of different grades from different sources showed that the device was capable of matching similar PG binders and distinguishing between different grades. For example, the DART could match two PG 58-22 binders from different sources. Likewise, it could distinguish a PG 58-22 binder from a PG 64-22 binder or a 70-22 binder.

- Tests using unaged samples from construction projects in two State DOTs, one in the Southeast and one in the Midwest, showed that samples failing to comply with the AASHTO M 320 specification could be identified based on a comparison with samples that satisfied the specification requirements. In State 1, the AASHTO M320 requirement for the pressure-aged vessel (PAV) sample was not satisfied by one of the binders, and in State 2 several samples did not meet the AASHTO M 320 Dynamic Shear Rheometer (DSR) test specification for the unaged binder. These validation tests showed that the DART successfully identified a deviation in the fingerprints to show lack of consistency compared to the certified binder. These results clearly validate that if used on samples collected more frequently, the DART improves the ability to detect binder non-compliance, which has hitherto not been an option because of long testing times and the inability to test at field laboratories.
- Tests on samples from an asphalt binder production facility showed that the trends in viscosity were evident and there is potential for use in a binder optimization process. Extensive testing and validation will be required to establish a procedure for this application.

Based on the results of this study, the DART device is proposed as an effective tool for process control of asphalt binders to enable larger sampling rates and faster testing of asphalt binders. Testing can be completed in as few as 2.5 hours with minimal operator time or skills. In its current stage of development, the DART can supplement, although not replace, AASHTO M 320 PG specification testing. It provides a means to verify consistency or deviation from certified samples.

BENEFIT TO THE STATE DEPARTMENTS OF TRANSPORTATION

The implementation of the DART device may offer several benefits for the various stakeholders involved:

- Simple and quick testing to detect deficient quality.
- Reduced risk of premature pavement failures for owners and the traveling public.
- Lowered risk of accepting inferior materials for owners.
- Lowered risk of litigation between suppliers, contractors, and owners.
- Cost savings for suppliers and owners resulting from optimized full-scale standardized testing using the DART as a screening device.
- Generation of data previously unavailable to advance the understanding of binder science.

This study did not make any strides with the actual implementation of the device in practice. However, it provided the much-needed data evidence and device refinements to support field implementation. The results suggest that the implementation potential is high, and the target uses include sample compliance checks at field and district laboratories, agency verification at HMA production plants, and consistency checks along the supply chain.

Figure 17. DART prototype for field testing and binder testing setup.