TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

IDEA *Innovations Deserving Exploratory Analysis Project*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Report of Investigation

NCHRP-IDEA
Report of Investigation 17

Prepared for
the IDEA Program
Transportation Research Board
National Research Council
Contract NCHRP-94-ID017

DEVELOPMENT OF SELF-CONTAINED PORTABLE DEVICE FOR SHRP BINDER TESTING: FIELD QUALITY CONTROL/QUALITY ASSURANCE TESTING WITH DUOMORPH ASPHALT RHEOLOGY TESTER

Prepared by:
Samuel H. Carpenter and Jag Mallela
Civil Engineering Department
University of Illinois

October 1996

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea)

DEVELOPMENT OF SELF-CONTAINED PORTABLE DEVICE FOR SHRP BINDER TESTING: FIELD QUALITY CONTROL/QUALITY ASSURANCE TESTING WITH DUOMORPH ASPHALT RHEOLOGY TESTER

CONTENTS

INTRODUCTION

The Strategic Highway Research Program (SHRP) was tasked with producing a specification for asphalt binders that resist rutting, fatigue, and thermal cracking. The specification, which had to be based on relationships of the measured property with the theoretical development of these distresses and supported by field validation, was the most innovative step in asphalt testing in a long time.

The SHRP specification establishes ranges in which a binder can be expected to perform well. The separation of binders into these ranges is done entirely with rheological testing. The dynamic shear rheometer (DSR) is used to perform rheological testing on original binders as well as on binders subjected to the rolling thin film oven (RTFO) and pressure aging vessel (PAV) tests. The data collected include the complex modulus values, G', G'', and G, and the phase angle, δ. Details regarding DSR testing can be found in SHRP Report SHRP-A-370 (*1*). The current SHRP specification for one grade of asphalt cement is described in Figure 1. The unique aspect of the specification is that the stiffness of the binder is a constant—only the temperature for each test is varied to maintain the stiffness value at the preset level. All asphalt cements are expected to produce the same stiffness level to satisfy performance at the expected temperatures for a given area.

Several approved DSR devices comply with the strict SHRP requirements. However, these devices are expensive, bulky, and confined to use in a highly controlled laboratory environment. Operational difficulties common to these devices are sample trimming and precise gap setting. DSR devices require

Performance Grade	PG-64				
	-16	-22	-28	-34	-40
Average 7-day Maximum Pavement Design Temperature	<64				
Minimum Pavement Design Temperature	>-18	>-22	>-28	>-34	>-40
Original Binder					
Flash Point Temperature AASHTO T48, min, C	230				
Viscosity, ASTM D422, max 3 Pa-S (3000 cP), Test Temp, C	135				
Dynamic Shear, SHRP B-003 G*/Sinδ, min 1.0 kPa Test Temperature @10 rad/sec, C	64				
Rolling Thin Film Oven Test					
Max Loss, %	1				
Dynamic Shear, SHRP B-003 G*/Sinδ, min 2.2 kPa Test Temperature @10 rad/sec, C	64				
Pressure Aging Vessel Residue (SHRP B-005)					
PAV Aging Temperature, C	100				
Dynamic Shear, SHRP B-003 G*/Sinδ, max 5000 kPa Test Temperature @10 rad/sec, C	28	25	22	29	16
Creep Stiffness, SHRP B-002 S, max, 300,000 kPa. m value, min 0.3, Test Temperature, C	-6	-12	-18	-24	-30
Direct Tension, SHRP B-006 Failure Strain, min 1.0% Test Temperature, C	-6	-12	-18	-24	-30
Physical Hardening Index	Report				

FIGURE 1 Sample SHRP specification for asphalt binder testing.

that geometry and testing conditions be precisely controlled for accurate asphalt binder testing. These requirements exclude some composite or filled binders from the test because some filler particles may exceed the spacing restrictions required for DSR use. Further, cold-temperature testing cannot be performed using standard DSR devices, which prevent the collection of a consistent set of material properties over an entire temperature range. The low-temperature evaluation of asphalt binders is done using the bending beam rheometer (BBR). It is preferable to use the same device to perform testing over the full range of SHRP temperatures.

The current versions of SHRP devices represent a significant step forward in asphalt technology. Limitations of the aforementioned equipment must be addressed in future refinements of SHRP equipment and testing protocols without compromising the data used to establish current specification parameters. This will ensure that field quality control/quality assurance (QC/QA) testing will have the same accuracy and implications as laboratory testing. It is likely that another testing device is needed to accomplish this and should be developed to advance and expand SHRP testing in the future. This report presents a potential device developed from existing technology.

In the 1970s Briar et al. (*2*,*3*) investigated the use of a piezoelectric (PZT) crystal assembly, the duomorph, as a permanently embedded sensor for long-term surveillance of the structural integrity of solid rocket propellant. Their study concluded that the duomorph makes it feasible to determine the dynamic mechanical properties of solid rocket fuel. Encouraged by this research, Bogess (*4*) and Lavoie et al. (*5*,*6*) have extended the concept, with considerable success, to determining complex moduli of asphalt concrete and marine sediments, respectively. These studies indicate that the duomorph has the potential to function as a low-cost, durable, and portable supplemental testing device for the DSR. Further, because it has the capability to replicate SHRP testing currently performed in the laboratory using the DSR, there is no concern that surrogate testing procedures will produce anomalous data. The duomorph has the potential to function over the entire temperature range in SHRP binder grading, extending to the lowest pavement temperatures expected and still providing the same rheological data, not an adjusted value. In addition, the duomorph is an implantable device capable of performing long-term viscoelastic monitoring regardless of binder composition.

The objective of this research, which is funded by NCHRP-IDEA Contract NCHRP-94-ID017, was to fabricate and evaluate a duomorph testing device, the Duomorph Asphalt Rheology Tester (DART). This objective was accomplished through a logical redevelopment of duomorph technology with suitable adjustments, refinements, and advancements to fine-tune it for asphalt binder testing. The fine-tuning involved evaluating new PZT materials for use in the duomorph, studying optimal sizing of duomorph sensors, and using improved electronic data acquisition technology. Initial evaluation was performed using the DART assembly on a SHRP-referenced asphalt binder to demonstrate the applicability and durability of the duomorph gauge in asphalt binder testing and to determine refinement and development potential for a complete field-ready package suitable for use by state departments of transportation for QC/QA testing in the field.

THE DUOMORPH

Operational Principles

The duomorph sensor is a bending plate device consisting of a stainless steel disk sandwiched between two concentrically mounted PZT ceramic crystals, as shown in Figure 2. The PZT crystals, which function as electromechanical transducers, are capable of producing electrical voltage when a mechanical deformation is applied to them and vice versa. A PZT crystal deforms (i.e., expands or contracts) when voltage is applied to it. In an electrically asymmetric duomorph, the poling axes of the two PZT crystals are oriented so that when voltage

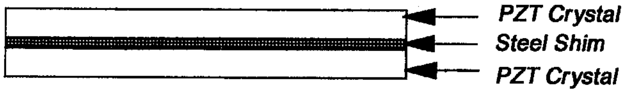

FIGURE 2 The duomorph sandwich.

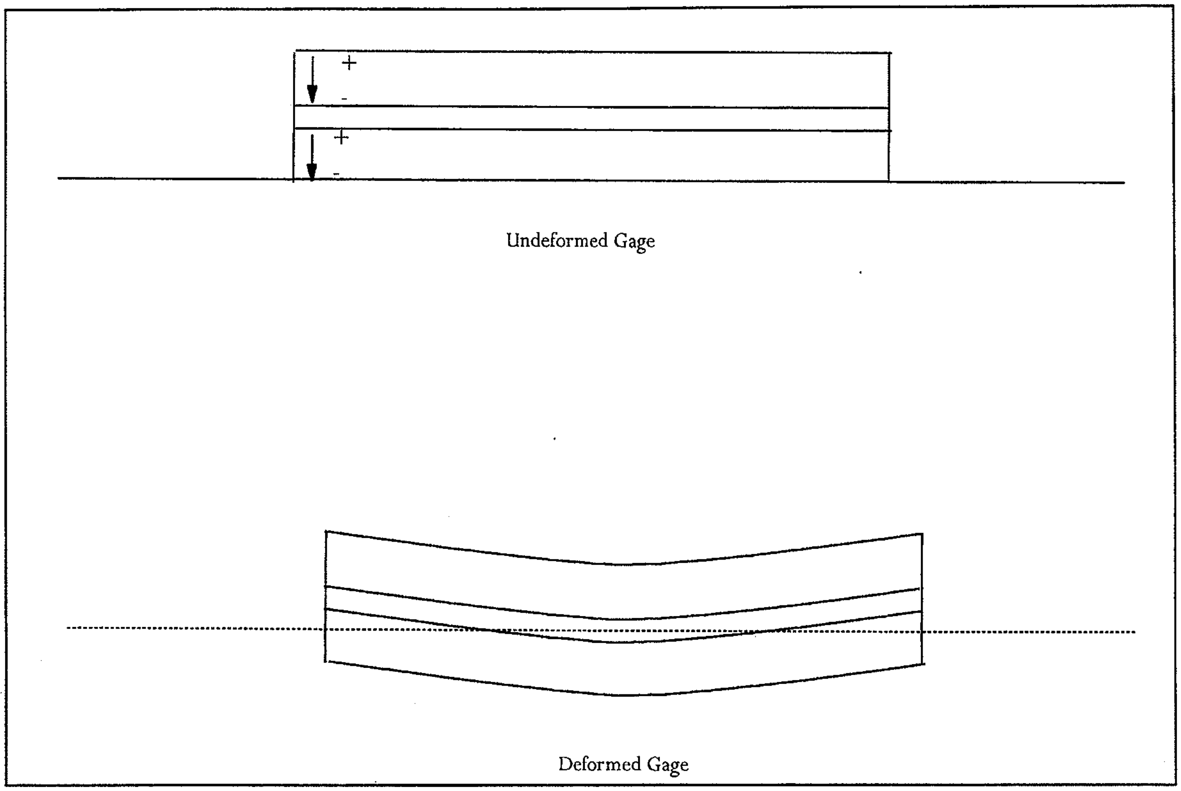

FIGURE 3 Gauge response before and after the application of a voltage signal.

is applied across their electroded faces, they deform in concert—one expands while the other contracts. This produces a bending action, as indicated in Figure 3. The deformation is parabolic in shape and directly proportional to the driving voltage.

If the applied voltage signal is sinusoidal, the sensor vibrates sinusoidally at the same frequency as that of the input signal. When air is the surrounding medium, the bending strain of the sensor should follow the trace of the driving voltage exactly, providing a calibration. However, when the sensor is embedded in a viscoelastic medium, such as an asphalt binder, there are two significant changes in the signal. First, a lag is induced in the response of the sensor with respect to the applied voltage signal. Second, the peak strain is reduced because of the confining effect of the stiffness of the surrounding medium. The lag in the response signal can be interpreted as the phase angle. Figure 4 depicts duomorph operation, illustrating phase angle determination. The ratio of peak sensor strains obtained during operation in air and operation in a viscoelastic medium provides the means to calculate the complex modulus values of the medium. In the current version of DART, the strains are recorded through strain gauges mounted on the sensor.

In a future iteration, it will be possible to use the PZT signal coming from the deformed gauge as the signal for deformation calculation, eliminating the need for strain gauges. The frequency of vibration can be set to match the rate of shear in DSR testing and can be continuously varied for complete material characterization.

Analysis of the Duomorph Sensor

In their pioneering work, Briar et al. (*3*) performed a quasi-static analysis to correlate the measured gauge strains and the viscoelastic properties of the continuum. Relevant parts of their analysis are included in this report. Though the duomorph is treated as a surface-mounted gauge as well as an embedded gauge in the

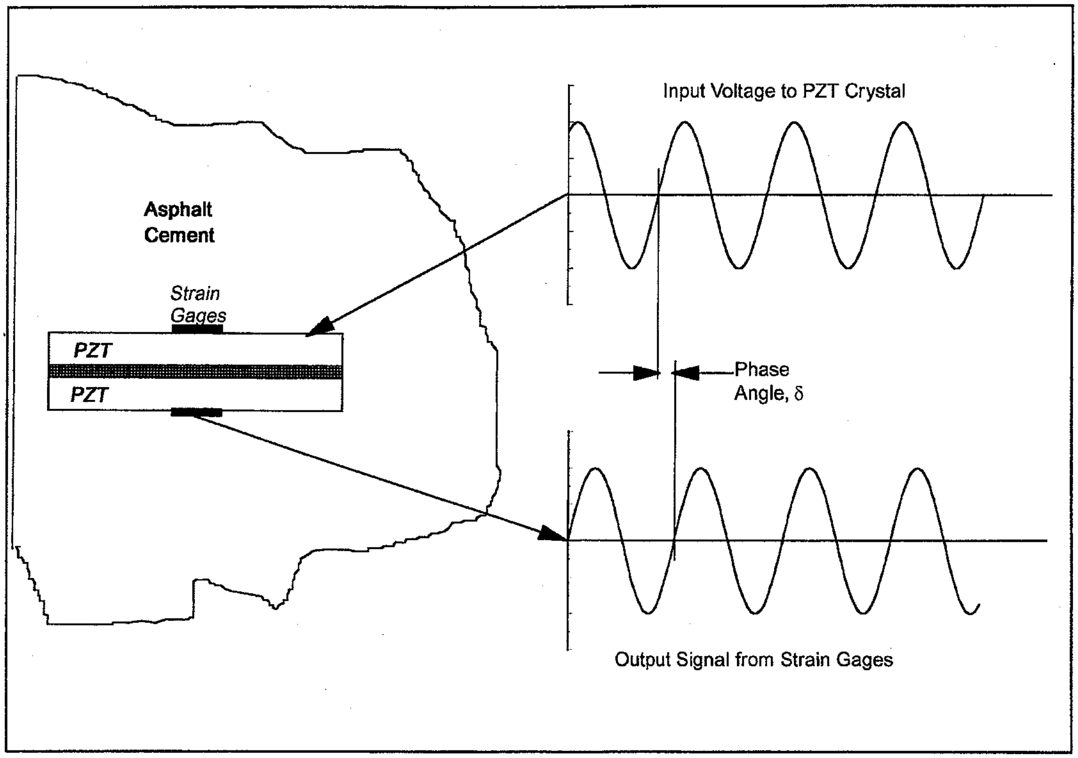

FIGURE 4 Phase angle determination of duomorph operation.

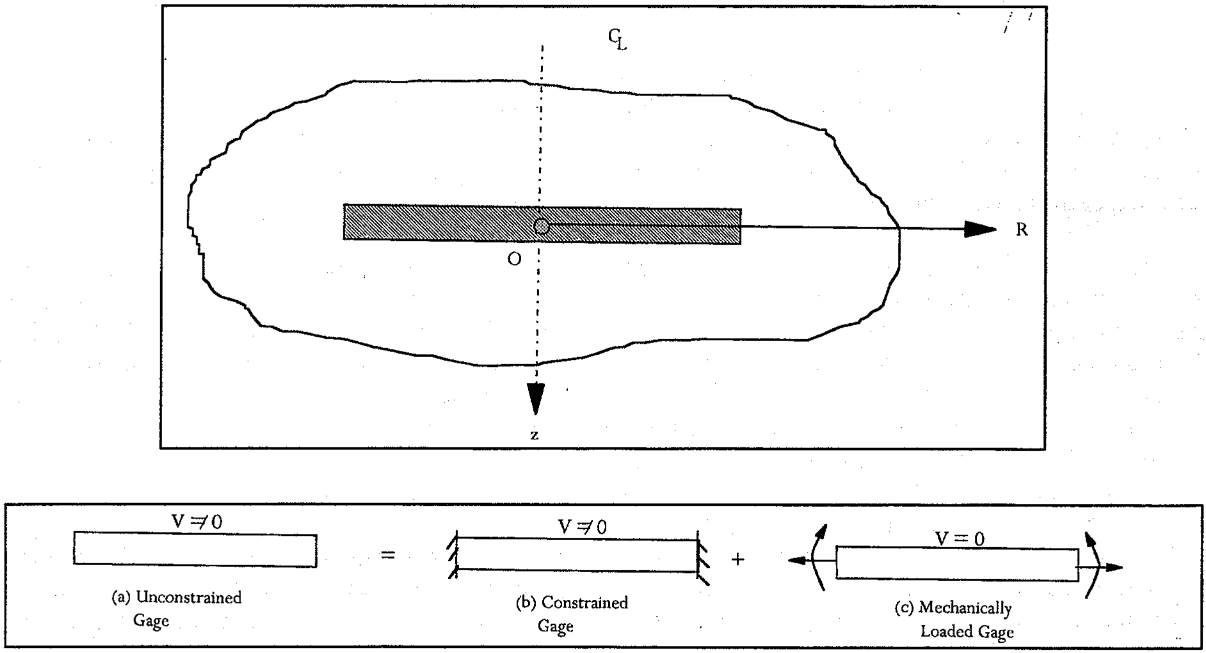

FIGURE 5 ***Top:*** **Gauge embedded in a uniform medium [adapted from Briar et al. (*3*)].** ***Bottom:*** **Equivalence of loading conditions [adapted from Briar et al. (*3*)].**

original referenced work, this report deals only with the latter application of the sensor.

The following assumptions were made in performing the initial analysis: classical thin plate theory fully describes the behavior of the duomorph and the continuum is initially assumed to be linearly elastic and infinite in extent. It also was assumed that inertial effects are negligible for operational frequencies below 500 Hz and that the continuum stresses and deformations produced by the gauge are significant only to within a cube of material, with an edge length equal to twice the gauge's diameter. In the analysis that follows, the duomorph gauge is treated as a circular thin plate, and the cylindrical coordinate system (R, θ, z) is used.

There are three steps in the analysis that leads to establishing a relationship between the measured strains of the duomorph and the continuum properties. The first step is to predict the response of an infinite elastic body subject to arbitrarily distributed normal traction from an interior point. From the theory of elasticity, the axial or z-displacement of the elastic continuum due to a distributed pressure, P, acting in the $z = 0$ plane (Figure 5, *top*) is given by the expression

$$w(R',o) = w_o = \frac{3R'}{4\pi\hat{E}}[I_1 + I_2] \tag{1}$$

where

$$\hat{E} = \frac{(1-\nu)E}{(1+\nu)(1-\frac{4}{3}\nu)} \tag{2}$$

$$I_1 = \int_0^1 P(R'\,x_1^{1/2})\,K(x_1)\,dx_1 \tag{3}$$

$$I_2 = \int_{(R'/a)^2}^{1} x_2^{-3/2}\;P(R'x_2^{-1/2})\,K(x_2)\,dx_2 \tag{4}$$

where
R' = radial distance from the center of the plate,
E = Young's modulus of the continuum, and
P = pressure distribution on the gauge.

The function $K = K(x)$ is a complete elliptic integral, which is defined as

$$K(x) = \int_0^{\pi/2} (1 - x\sin^2\phi)^{-1/2}\,d\phi \tag{5}$$

To evaluate the integrals I_1 and I_2, the pressure distribution, P, should be known. However, because this pressure is a function of the gauge displacement, it is not known a priori. To offset this difficulty, a piecewise constant pressure distribution scheme is assumed. Under this scheme, the gauge is divided into a central area and a series of N concentric rings. This leads to the expression of the total displacement as a summation of a finite set of constants, which greatly simplifies the solution.

The next step is to analyze the unconstrained duomorph gauge to establish a companion set of relationships linking displacement and pressure. Within the context of classical plate theory, applying voltage to the gauge on the bending strains and deflection are equivalent to applying a concentrated edge moment, M_0, around the gauge's periphery (Figure 5, *bottom*). In the absence of any other load, the plate deflection, w_m, in the z direction, caused by the moment, M_0, acting at the edge $R = a$, from classical plate theory (*6*) is given by the expression

$$w_m = \frac{M_0\,a^2}{2D\,(1+\nu)} + (1 - \frac{R^2}{a^2}) \tag{6}$$

where
R = distance from the center of plate at which deflection is measured,
a = plate radius,
ν = plate Poisson's ratio, and
D = plate flexural rigidity given by the expression

$$D = \frac{E_z\,h^3}{12(1-\nu^2)}[1 + (\frac{E_m}{E_z} - 1)(\frac{h_m^3}{h})] \tag{7}$$

where
E_z = modulus of the PZT wafer,
E_m = modulus of the steel shim,
h_m = thickness of steel shim, and

h = overall thickness of the duomorph.

In Equation 6, when R equals a, the gauge displacement is arbitrarily taken as zero.

Finally, the consideration of equilibrium in the gauge-continuum interaction analysis leads to the following matrix expression, which is expressed entirely in terms of nondimensional quantities:

$$[W]\,\{q\} = \{I\} \qquad \textbf{(8)}$$

The column vector, $\{q\}$, represents the set of unknown nondimensional pressures. $\{I\}$ is a column vector with components specified as follows:

$$I_i = \frac{1}{2(1+\nu)}\left(1 - \frac{i-1}{N}\right) \text{ for } i = 1, 2, \ldots, N+1 \qquad \textbf{(9)}$$

N is the number of circular segments into which the disk is divided. The elements of the (N+1) by (N+1) square matrix, $[W]$, are defined as

$$w_{ij} = \frac{3a_{ij}}{2\pi\hat{M}\sqrt{N}} + \frac{b_{ij}}{32N} + c_{ij} \qquad \textbf{(10)}$$

M is a dimensionless parameter providing a relationship between continuum stiffness and gauge stiffness, and a_{ij}, b_{ij}, and c_{ij} are matrix constants. $\hat{M}$ is given by the expression

$$\hat{M} = \hat{E}\,a^3 / D \qquad \textbf{(11)}$$

After the vector, $\{q\}$, is computed from Equation 8, the quantities of interest in applications of the gauge, such as M_c/M_0, can be computed analytically from plate theory. This moment ratio is a complex value comprising both the amplitude $|M_c/M_0|$ and phase θ_M. It can be represented in the polar form as

$$\frac{M_c}{M_0} = \left|\frac{M_c}{M_0}\right| e^{-i\theta_M} \qquad \textbf{(12)}$$

M_c and M_0 stand for plate central moment and applied edge moment, respectively. The magnitude of the moment ratio is related to the measured strains as follows:

$$\left|\frac{M_c}{M_0}\right| = \left|\frac{\varepsilon_c}{\varepsilon_a}\right| \qquad \textbf{(13)}$$

ε_c and ε_a are strains at the center of the duomorph in the continuum and air, respectively. This expression holds true for a symmetrically driven duomorph, which is the duomorph under consideration.

Extension to Viscoelasticity

Although the derivations illustrated to this point are premised on an elastic medium, the solutions are not limited to determination of elastic continuum properties. Extension of the analysis to viscoelastic behavior is accomplished by applying the correspondence principle. This application requires the substitution of $\hat{M}$ with $\hat{M}^*$ and ν with ν^*. The complex parameter $\hat{M}^*$ may be written in rectangular form as

$$\hat{M}^* = \hat{M}' + i\hat{M}'' \qquad \textbf{(14)}$$

where i equals $\pm\sqrt{1}$ and $\hat{M}'$ and $\hat{M}''$ are real and imaginary parts of $\hat{M}^*$, respectively. Also from Equation 11, it follows that

$$\hat{M}' = \hat{E}'a^3 / D \qquad \textbf{(15a)}$$

$$\hat{M}'' = \hat{E}''a^3 / D \qquad \textbf{(15b)}$$

$$\tan\phi = \hat{E}''/\hat{E}' \qquad \textbf{(16)}$$

Once E' and E'' are determined, the complex modulus can be determined employing the relationship

$$E^* = \sqrt{E'^2 + E''^2} \qquad \textbf{(17)}$$

The shear modulus, G^*, is then given by the expression

$$G^* = \frac{E^*}{2(1 + \nu^*)} \qquad \textbf{(18)}$$

Of all the parameters presented in Equations 1 through 18, the only parameter that can be determined readily in the laboratory is the modified moment ratio from Equation 13. When this ratio is known, it is possible, in theory, to back-calculate the real part of the nondimensional stiffness parameter, $\hat{M}'$, and subsequently E^* and G^*, employing Equations 1 and 8. However, this is not a pragmatic approach that lends itself to straightforward solutions for determining material property. Therefore, a nomograph such as the one shown in Figure 6 is constructed numerically. This nomograph is constructed from two families of curves sharing an independent axis. The first family of curves plots the magnitude of the modified moment ratio $|M_c/M_0|$ against $\hat{M}'$ for various values of the loss tangent, tan ϕ. The second plots θ_M, the phase shift induced in the response of the duomorph to the medium, against $\hat{M}'$ again for various values of tan ϕ. Using this nomograph, with values for both the modified moment ratio and the phase angle θ_M, solutions for $\hat{M}'$ and tan ϕ can be determined iteratively. By employing these values with Equations 15 through 18, viscoelastic properties of the continuum required for SHRP binder grading can be obtained.

Equipment Requirements

To provide the data necessary to perform the calculations described previously, the following requirements must be met:

- A precisely controlled voltage signal must be provided as the driving signal for the PZT crystals.
- A precision signal generator must produce accurate and stable frequency control for the driving voltage signal.
- Strain gauge amplifier and signal conditioners must produce accurate, stable voltage signals both to and from the strain gauges.
- A means must be provided for recording the input and output voltage signals over time.

When these requirements are fulfilled, the complex modulus and phase angle can be calculated.

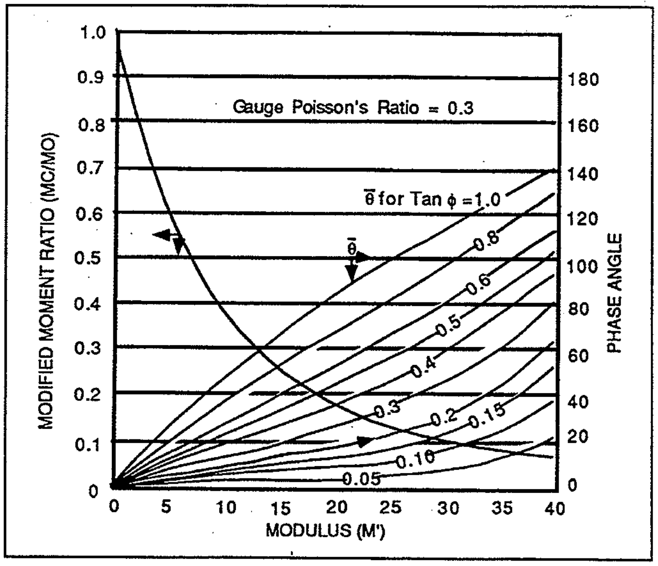

FIGURE 6 Typical nomograph for DART data reduction.

Data Reduction

The following data reduction steps were followed to obtain SHRP parameters from duomorph testing using the nomograph:

1. Obtain the strain at the center of the duomorph disk for a given voltage and frequency of testing in air and in asphalt—ε_a and ε_c, respectively.
2. Obtain the phase difference between the sinusoidal voltage input and the corresponding strain output in air as well as in asphalt,—θ_a and θ_c. The phase angle for the medium is then calculated as $\theta_M = \theta_c - \theta_a$.
3. For the given duomorph disk, establish the disk rigidity parameter, D.
4. Employing Equation 13, determine the modified moment ratio $|M_c/M_0|$.
5. Enter a nomograph such as the one shown in Figure 6 with the moment ratio from Step 4 and the phase angle from Step 2, and iteratively determine the values of $\hat{M}'$ and tan ϕ. Iterate until the differences between the respective parameters obtained from two successive steps fall within acceptable limits.
6. Using $\hat{M}'$ and tan ϕ obtained from Step 5, employ Equations 15a and 16 to compute E' and E'', respectively. Compute E^* and G^* from Equations 17 and 18, respectively.

The data reduction procedure contains several time-consuming the steps, most notable of which are (*a*) constructing a nomograph for the specific duomorph gauge under consideration and (*b*) performing iterations to obtain the desired moduli. The DUONOMO and DUO_CALC computer programs, developed by Grosz (*7*) as part of the Office of Naval Research effort to conduct marine sediment testing, help expedite the data reduction process. The DUONOMO program numerically constructs the nomograph for any given disk geometry, and the DUO_CALC program uses this to compute $\hat{M}'$ and tan ϕ iteratively. The inputs for the DUO_CALC program are the measured strains and phase angles in air and in asphalt. These programs, which are in the public domain, can be used for constructing nomographs for each duomorph gauge and are not required for every calculation.

Alternatively, Briar et al. (*2*) suggest using the following simplified expression for data reduction. This expression, which is particularly useful for low-modulus applications, relates the complex modulus of the continuum to the voltage ratios, phase angles, and the disk rigidity factor, *D*.

$$E^* = \frac{12.23D}{a^3}\left[\frac{(V_{ic}\ /V_{Rc})}{(V_{ia}\ /V_{Ra})}\ e^{-i(\theta_c - \theta_a)} - 1\right] \tag{19}$$

where V_{ic} and V_{ia} are the amplitudes of input voltages in asphalt and in air, respectively, and V_{Rc} and V_{Ra} are the amplitudes of output voltages in asphalt and in air, respectively.

This expression, which greatly simplifies the data reduction process, was used in this study to reduce data resulting from testing of asphalt binders that fall into the low-modulus range as suggested by Briar. Comparisons with nomographic solutions indicate insignificant differences between the two methods.

THE DART ASSEMBLY

The DART assembly consists of the electronic components listed previously to activate and obtain data from the duomorph sensor. Figure 7 illustrates the necessary arrangement of components to establish a fully functional DART system. The two major tasks in component assembly are (*a*) designing optimally sized duomorph gauges for the medium being tested and (*b*) assembling suitable electronic subsystems capable of driving and obtaining data from the duomorph.

Gauge Design

Gauge design involves selecting appropriate dimensions for thickness and diameter and materials for the PZT crystals and steel shim to ensure that proper output and stiffness matching is obtained for any given asphalt binder. Because the SHRP specification requires a stiffness level, the same duomorph will function equally well for all grades of asphalt at a given processing level. However, it may be necessary to have different gauges

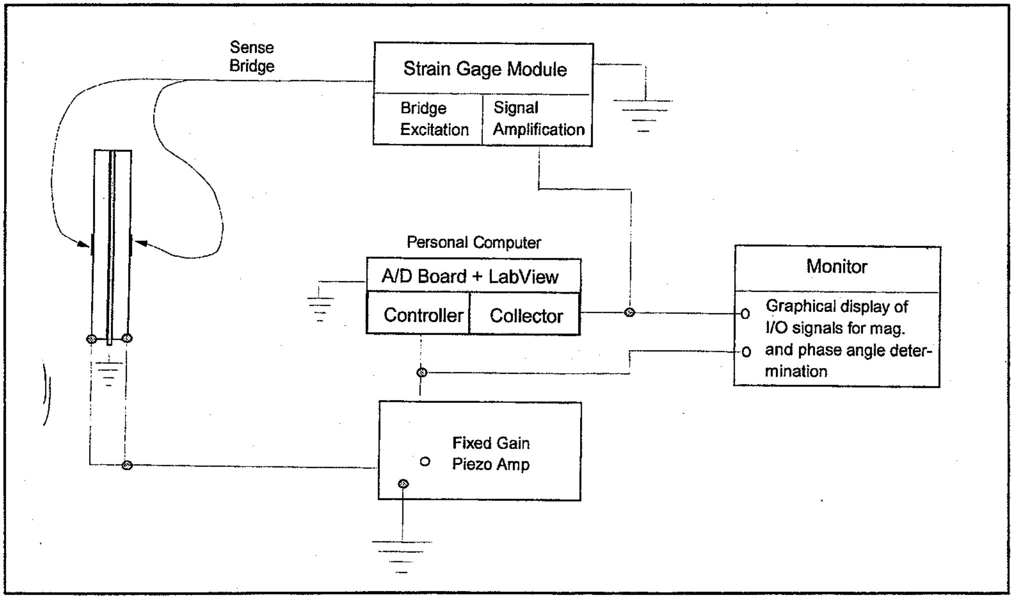

FIGURE 7 Typical DART setup.

for the tank and RTFO-processed and PAV-processed materials because the stiffness levels for each of these processing levels are different.

The operating characteristics needed to achieve a predetermined strain level during testing for SHRP compliance also must be determined by carefully considering gauge rigidity and driving voltage level. Theoretical relationships can be used to establish desirable dimensions, but actual testing of various combinations more fully demonstrates the suitability for asphalt testing. Therefore, several duomorph gauges with dimensions shown in Table 1 were assembled and tested at various voltage levels. The rigidity parameter, *D*, for each gauge also is listed in Table 1. Strain gauges with presoldered leads with a resistance of 350Ω were affixed at the centers of the PZT crystals in a half-bridge configuration to measure strain in the duomorph during operation. The strain gauges, with overall dimensions of 0.25 cm by 0.125 cm, were capable of measuring strains up to 5 percent. Their practical operating temperatures ranged from -75 °C to 175 °C. An external strain gauge signal conditioning module was provided to supply the required bridge completion, excitation, and gain. Power leads were carefully soldered to both faces of the duomorph, and a ground wire was soldered to a small tab projecting from the central steel shim. A fine thermocouple was affixed to the duomorph to monitor asphalt temperature during testing. Each gauge was given a serial number ranging from DART 1A through DART 3C (Table 1). Figure 8 presents several assembled DART devices.

TABLE 1 Dimensions and Flexural Rigidities of the Duomorph

Duomorph Nomenclature	Thickness, mm		Diameter, mm	Flexural Rigidity, D N-mm
	PZT	Steel		
DART # 1A	0.1905	0.2032	25.4	759.6909
DART # 1B	0.1905	0.2032	19.05	759.6909
DART # 1C	0.1905	0.2032	12.7	759.6909
DART # 2A	0.1905	0.1270	25.4	1228.4363
DART # 2B	0.1905	0.1270	19.05	1228.4363
DART # 2C	0.1905	0.1270	12.7	1228.4363
DART # 3A	0.1905	0.1016	50.8	641.6863
DART # 3B	0.1905	0.1016	25.4	641.6863
DART # 3C	0.1905	0.1016	19.05	641.6863

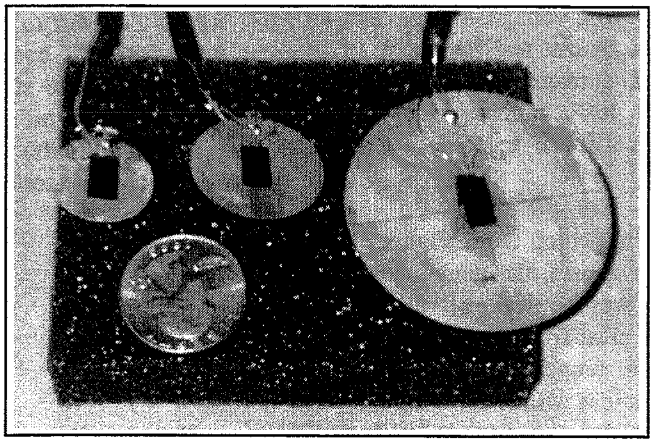

FIGURE 8 ***(from left)*** **Assembled DART devices, 2B, 2A, and 3A.**

Electronic Subsystem

The electronic subsystem consisted of a 66-MHz 486 personal computer equipped with a National Instruments AT-MIO-16E-2 ADT board. The functions of the computer and board included generating the drive signal that produced deformations in the duomorph gauge and acquiring the electronic signal from the strain gauges as the duomorph deflected. A precision external PZT amplifier with a fixed gain of 15 was required to amplify the ±5-V signal coming from the National Instruments ADT board. This combination produced a digitally controlled signal with precise control. A custom-designed program was developed using LabVIEW software (*8*) to drive the ADT board and to store the input and output waveforms in a spreadsheet format. Phase angles and peak strains subsequently could be obtained from the data stored and could be further processed using the data reduction scheme described previously to obtain the desired SHRP parameters. Figure 9 presents the various electronic components that make up the DART system.

CALIBRATION OF GAUGE RESPONSE

Initial evaluation of the duomorphs under consideration was done by testing them in air at various driving voltages and frequencies to (*a*) determine gauge behavior at various test frequencies to identify resonant frequencies and (*b*) provide a calibration for subsequent asphalt testing.

The gauges were tested at two peak-to-peak AC voltage levels: 35 and 70 V. At each voltage level, the gauges were tested at frequencies ranging from 0.5 to 1000 Hz. The best-fit curves of the ratio of strain gauge output voltage, V_{out}, to the driving voltage, V_{in}, at each of these frequencies is plotted against test frequency in Figure 10 for DART 2B. The magnitude of driving voltage does not affect the V_{out} to V_{in} ratio significantly, suggesting that the gauge has a linear response within this voltage range.

Another important observation from Figure 10 is that as the test frequency increases, the gauge output increases. This behavior was typical of all the duomorphs tested. It also was clear from the testing that the resonant frequencies of the gauges were well about 500 Hz. This finding suggests that within the frequency range of interest to asphalt testing (i.e., below 30 Hz), resonance is not a problem. Further, at these lower frequencies, a single calibration point may be sufficient given the small change in voltage ratio as frequency increases.

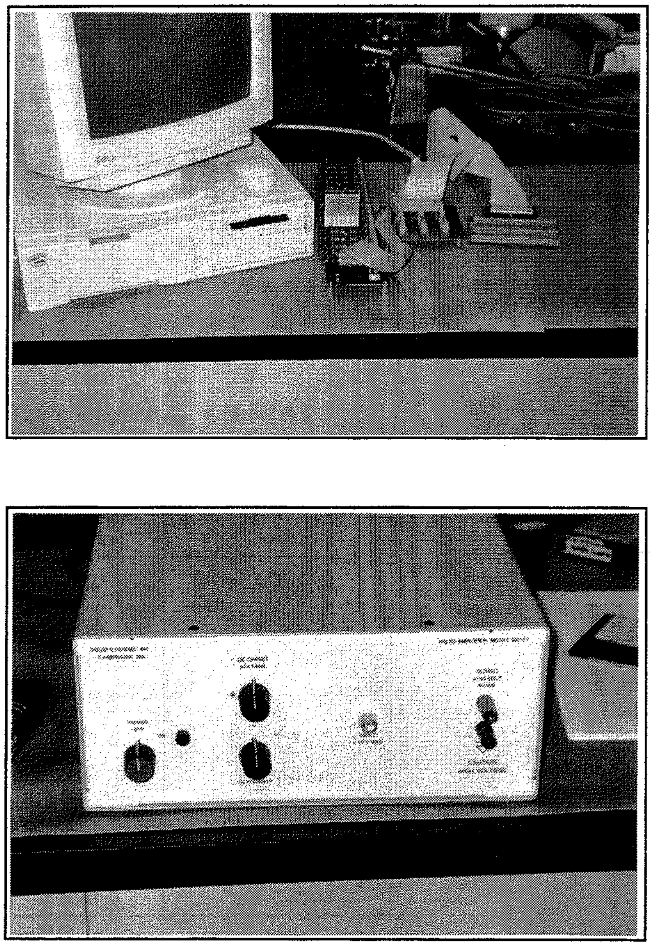

FIGURE 9 ***Top, left to right:*** **66-MHz 486 personal computer with ADT board and LabVIEW, 5B Series backplane with 5B38 strain gauge module, and SC-2050 cable adapter and CB-50 input-output connector (National Instruments).** ***Bottom:*** **EPA 101 PZT amplifier (Piezo Systems).**

ASPHALT BINDER TESTING

Testing of Tank Asphalts

Because the first use of the duomorph as a QC/QA test device will be for acceptance testing of tank asphalt cement, initial evaluation of suitability was conducted on an AC-20 tank asphalt. This asphalt was chosen because it was extensively evaluated for SHRP specification compliance in an earlier study at the University of Illinois and because its properties are known. A cylindrical asphalt specimen with a height and diameter of 4 in. was prepared. Each gauge was inserted into the specimen. Care was taken so that the gauge did not come close to the walls of the container holding the specimen. Gauge responses in the asphalt medium were collected at the same frequencies and driving voltages at which the air tests were performed. Temperature was varied from 30 °C to 60 °C in increments of 5 °C. Temperature control was established by placing the asphalt specimen in a digitally controlled water bath.

Data analysis showed that gauges with diameters of 2.54 cm or less were too rigid and not sensitive to the subtle modulus changes at temperatures in excess of 50 °C. In addition, the magnitude of the driving voltage did not affect the end result (i.e., shear modulus) significantly. Figure 11 presents the shear moduli of the tank asphalt obtained by reducing data from DART 3A at the various test temperatures and frequencies. Of all the gauges considered in this study, this one has the least rigidity and the maximum surface area; therefore, it provided the most sensitivity necessary for tank asphalt testing. For any given frequency, as the test temperature is reduced, the shear modulus increases. Similarly, at any given temperature, as the test frequency is increased, the modulus increases. These trends are consistent with theory and establish the feasibility of using the duomorph for modulus testing.

The magnitudes of the shear moduli obtained on the tank AC-20 from the DART, however, were found to be much higher than those obtained from the DSR. Figure 12 presents a comparison of the shear moduli obtained from the DSR and the DART system at 55 °C. The DSR tests were performed at the University of Illinois using the PAAR-Physica rheometer. The phase angles obtained from the DART system at this temperature were significantly different from those obtained using the DSR. This discrepancy is due primarily to the fact that even the DART 3A duomorph gauge is too rigid to make accurate modulus measurements at this temperature and that the current design lacks the necessary sensitivity to collect phase angle data at this high temperature.

As the test temperature was dropped from 60 °C to about 30 °C, the agreement between DSR and DART results gradually improved. Figure 13 presents the progression of asphalt stiffness with falling temperature as measured by the DART and DSR devices. The test frequency was fixed at 1.59 Hz. Table 2 presents the corresponding phase angle data. At about 34 °C, both devices measure comparable modulus and phase angle.

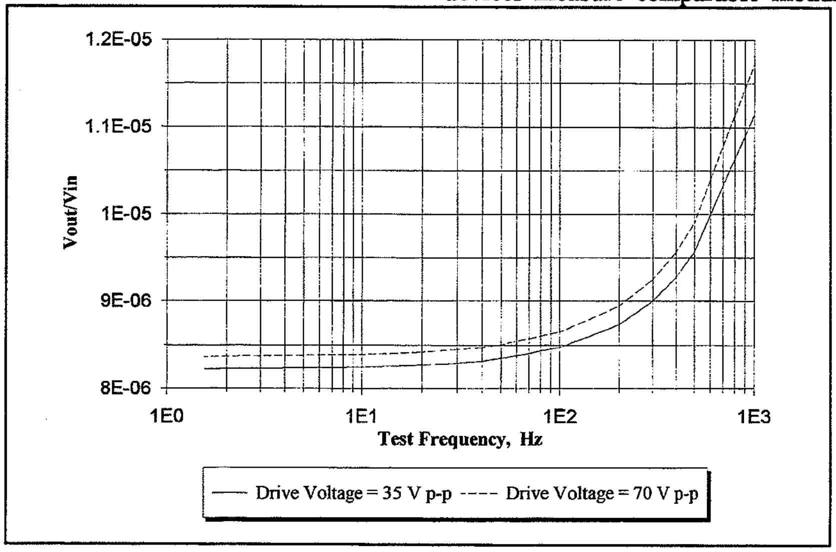

FIGURE 10 Operational characteristics of DART 2B.

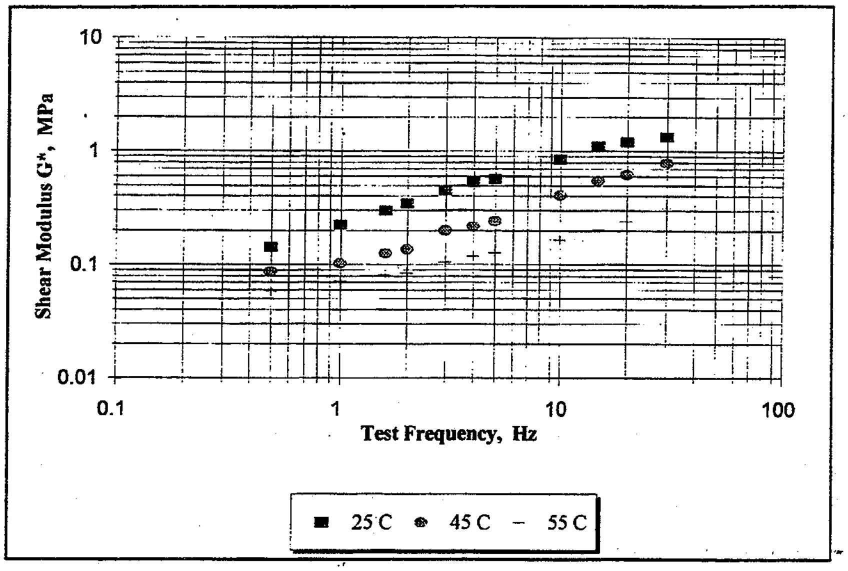

FIGURE 11 AC-20 tank asphalt binder test results using DART 3A.

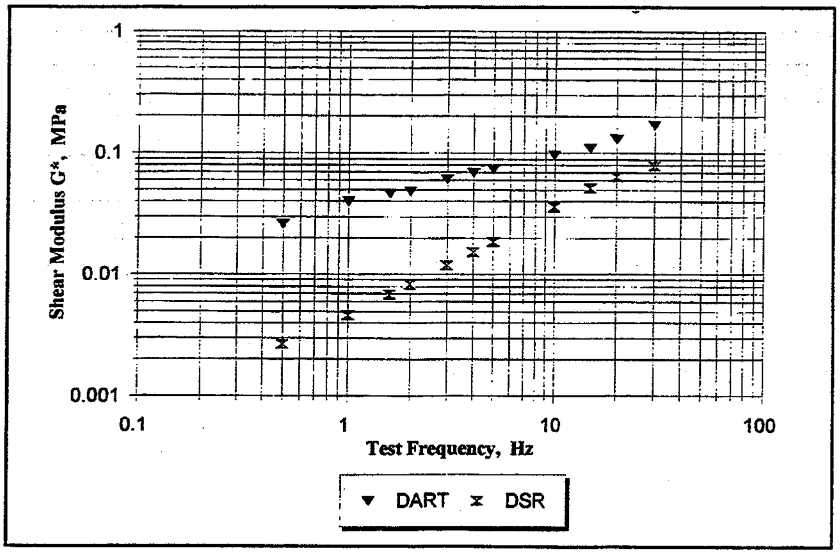

FIGURE 12 Comparison of shear moduli at 55°C for an AC-20 tank binder.

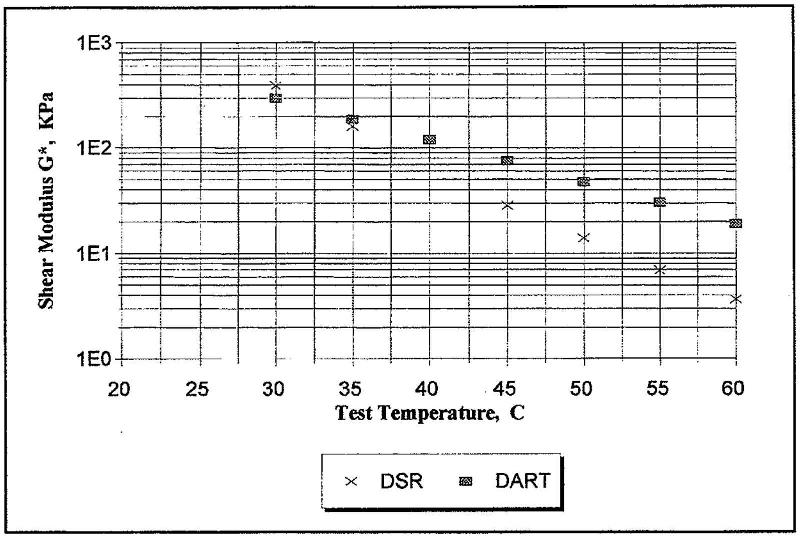

FIGURE 13 ***G**** **versus temperature at 1.59 Hz for an AC-20 tank asphalt.**

TABLE 2 Comparison of Phase Angles Obtained at a Test Frequency of 1.59 Hz for an AC-20 Tank Binder

Test Temperature, C	Phase Angle, degrees	
	DART	DSR
25	34.34	37.51*
30	27.51	45.0
45	21.75	83.61
50	16.61	85.19
55	13.34	85.56
60	10.56	86.73

* The phase angle at this temperature point was extrapolated from the general trend of the data.

The increasing phase angle from the DART as the temperature is dropped indicates the ability of the duomorph gauge to sense the surrounding medium as it becomes stiffer. This particular duomorph requires the medium's stiffness to be in the range of 100 to 300 kPa for accurate modulus and phase angle determinations to be obtained. This suggests that DART 3A can be used for binder testing in this stiffness range. It can be hypothesized that for any duomorph gauge with a given rigidity, there exists a range of asphalt stiffness within which the duomorph can be expected to perform optimally.

This finding indicates that a duomorph gauge that is more flexible than DART 3A can be expected to perform better at temperatures in excess of 50 °C where the asphalt modulus is low and where initial SHRP testing must be performed. Manufacturing such a disk, however, would mean either adopting a different PZT material or using a thinner stainless steel shim. These activities are beyond the scope of this investigation and should be pursued in the next phase of equipment development. In January 1996 PiezoSystems, Inc., the supplier of previous materials, produced a duomorph assembly with only an epoxy layer separating and electrically shielding the two PZT disks. The use of a rigid stainless steel shim was eliminated in this construction. This gauge, with a significantly reduced rigidity, will be investigated to assess its capability to test tank asphalt binder. PZT plastics, which essentially are plastic analogs of PZT ceramics, have some features that are germane to this research and hence also will be considered.

Testing of PAV Asphalts

The SHRP-specified PAV test was performed on the tank asphalt specimen tested before. The PAV binder was tested using the DART gauges and the DSR at various frequencies and temperatures. The PAV sample was placed in a cylindrical container with a height and diameter of 2 in. Because earlier tests demonstrated that the magnitude of the driving voltage does not affect the output modulus, a peak-to-peak AC voltage of 70 was used in the PAV binder testing. This high driving voltage was necessary to ensure clean gauge output even

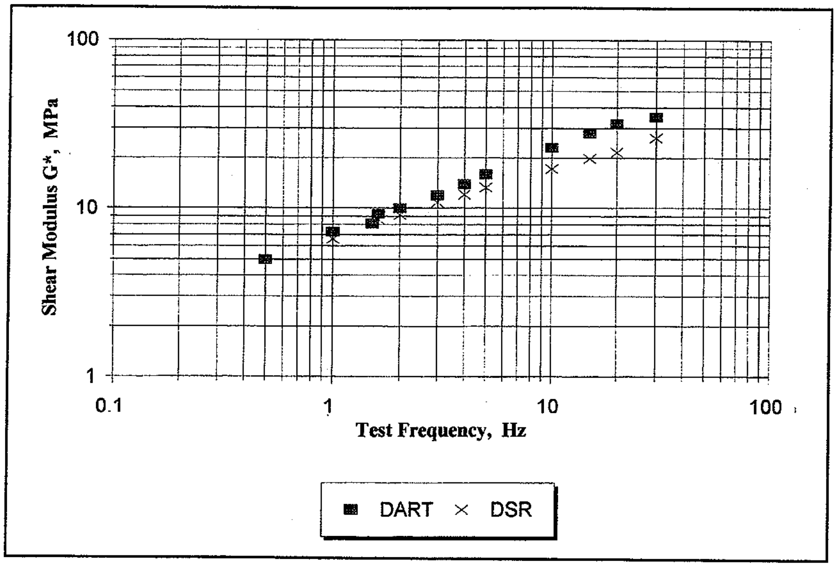

FIGURE 14 Comparison of shear moduli at 22° C for an AC-20 PAV binder.

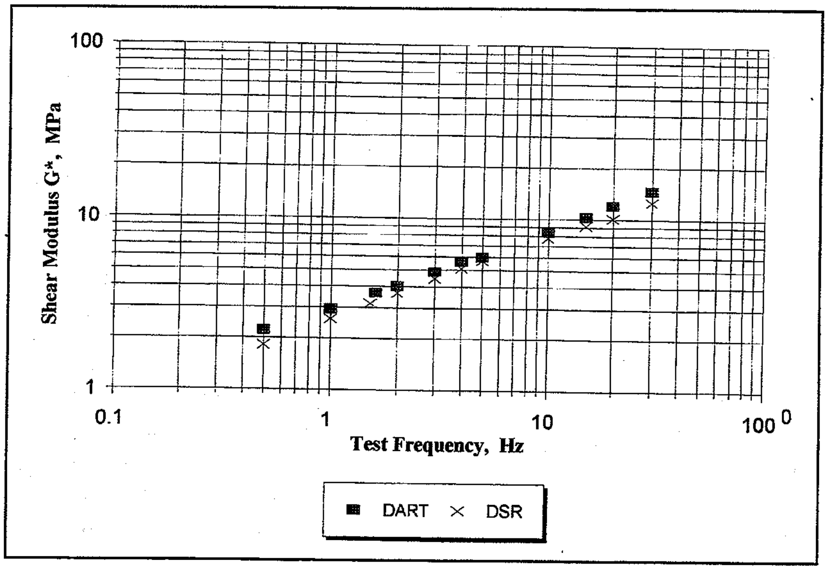

FIGURE 15 Comparison of shear moduli at 30 °C for an AC-20 PAV binder.

at the very low test temperatures required for the SHRP specification. Figures 14 and 15 compare the *G** values of the PAV material obtained from DART 2B with those obtained from the DSR at 22 °C and 30 °C, respectively. The results are similar. Table 3 compares the phase angles at various temperatures obtained from the two procedures at the frequency of interest (i.e., 1.59 Hz or 10 rad/sec). The excellent agreement at 22 °C and the mismatch at higher temperatures demonstrate the sensitivity that must be maintained in the electronics and measurement equipment and the importance of matching the DART assembly with the medium to obtain the accurate results required for SHRP binder testing. DART 2B is slightly stiff for higher temperatures but indicates that matching a gauge to a binder stiffness is possible. This finding fits into the SHRP testing scheme, which requires unique stiffness values at each stage.

The DSR test at the intermediate temperature establishes the low-temperature grade of asphalt cement and dictates the temperature at which the bending beam test and direct tension test must be conducted. The finding that the DART results match the DSR results closely at the intermediate temperatures, therefore, is significant and indicates that suitable duomorph designs can be obtained for testing the PAV material.

TABLE 3 Comparison of Phase Angles Obtained at a Test Frequency of 1.59 Hz for a PAV-Processed AC-20 Binder

Test Temperature, C	Phase Angle, degrees	
	DART	DSR*
22	42.3	42.2
25	38.2	44.9
30	32.1	48.7

* The phase angles in the DSR were measured at 1.5 Hz.

To demonstrate suitability for low-temperature testing, the PAV specimen was further tested using DART 2B at -18 °C, a typical low temperature for the performance grade-64 asphalt binder evaluated in this study. DART responses at 0.5, 1, and 1.59 Hz were collected and reduced to obtain the shear moduli. Collecting and reducing DART responses at frequencies lower than these will be possible with electronic data collection equipment, which was not available at the time of testing. To compare these numbers with the BBR test, the results of the BBR test must be converted from time to frequency domain. The BBR stiffness data typically are reported at a loading time of 60 sec, which corresponds approximately to a frequency of 2.65 MHz according to the following equation:

$$t = \frac{1}{2\pi f} \tag{20}$$

Figure 16 plots BBR stiffness data along with the stiffness obtained from DART 2B at the same temperature. Because the DART and BBR tests were not performed at the same frequencies, a dotted line, which represents typical BBR data, is plotted in the figure. This line is almost parallel to a more complete BBR data set from a previous study for a different AC-20 sample. This demonstrates that the DART moduli compare favorably with the BBR results. Better utilization of DART electronic data acquisition will facilitate improved testing and data collection at these low temperatures and thus will aid in a more direct comparison with the BBR tests.

Repeatability

The DART assembly provides an extremely stable platform for testing. This was illustrated in a series of repeatability tests, which included measurements made after removing the DART from and replacing it in the asphalt cement sample, bringing the sample to temperature, and recording the data for G^* and phase angle calculations. Table 4 contains the results, with the mean and standard deviation, of this testing. Although this testing cannot truly establish the precision of this piece of test equipment, it does indicate that the

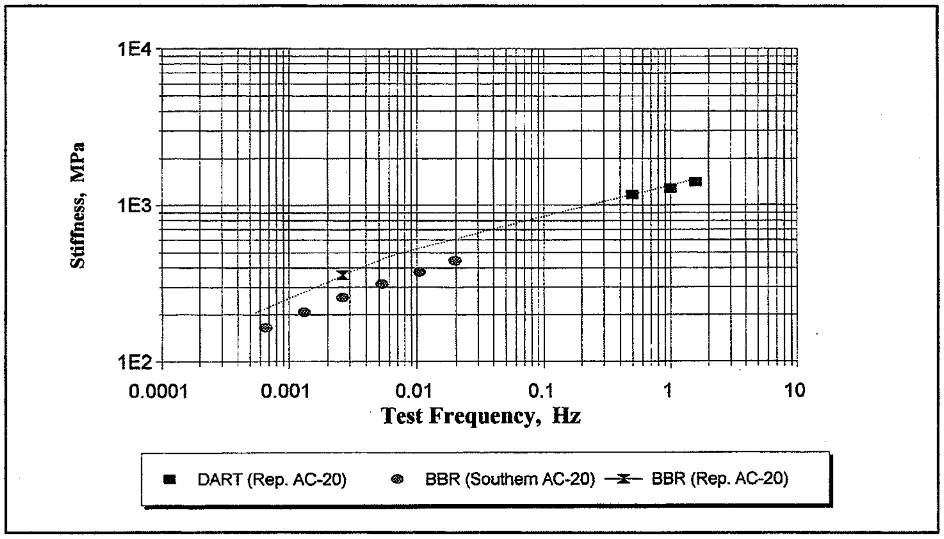

FIGURE 16 Comparison of bending stiffnesses at -18 ° C.

equipment is extremely repeatable and stable. Until a final set of duomorph gauges is designed, assembled, and tested, the true precision of the DART process cannot be fully established.

TABLE 4. Repeatability Evaluation of DART Assembly

Test Temperature	G*, MPa	Phase Angle, degrees
22 °C	9.29	42.36
	8.67	40.07
	9.53	37.21
	8.83	41.78
	7.73	41.21
	8.80	41.21
	10.90	41.71
	9.91	40.64
	$\sigma = 0.97$ $\mu = 9.16$	$\sigma = 1.57$ $\mu = 40.78$
25 °C	6.33	34.34
	6.49	32.63
	5.79	35.49
	$\sigma = 0.30$ $\mu = 6.21$	$\sigma = 1.18$ $\mu = 34.15$

STUDY FINDINGS

This program originated because of the need for a device capable of determining the SHRP parameters for asphalt binders in the field. As part of the study, the duomorph gauge was redeveloped for application in asphalt rheology testing. The DART system that evolved is the result of a continuous refinement process that addressed issues such as component assembly, data reduction schemes, electronics, and data acquisition. The feasibility of the system was judged by testing at various temperatures—50 °C to 60 °C (tank asphalts), 18 °C to 25 °C, and -28 °C to -12 °C (PAV-aged asphalts). The shear moduli and phase angles determined using the DART were verified by comparing results from the DSR and BBR, which indicates that a DART can be assembled with the required dimensions to determine SHRP compliance. Sensor ruggedness and durability also were under scrutiny. The following conclusions were reached:

- Reasonably priced equipment that collects data on asphalt binders has been assembled. The electronics, computer, and duomorph gauges can be assembled for less than $8,000. New water- and low-temperature controlled baths represent another $6,000 investment. DART gauge assemblies should cost approximately $800.
- Initial testing indicates that different gauge sizes, construction, or both will be required so that tank and PAV-aged materials match gauge stiffness to binder stiffness required for SHRP compliance.
- The *G** values and phase angles from PAV binder testing at intermediate temperatures obtained by using the DART 2B (3/4-in. diameter and 20 mils thick) agree with values collected by the PAAR-Physica DSR. Therefore, for measuring stiffness values in the SHRP specification, the DART is a low-cost, rugged, and viable alternative to the DSR that can be used in the field.
- Test results for tank asphalts at elevated temperatures were inconclusive because the size and rigidity of the disks available for this initial study were too small or too thick for these temperatures and for asphalt consistencies. Theory indicates that gauges that are more flexible can be used with some success at these temperatures.
- The *G** values from the DART at -18 °C are similar to BBR results.
- The duomorph device is not fragile and can withstand normal laboratory use for extended periods of time, which indicates that it can be used as a QC/QA device in the field, where the conditions are more severe.

Following are limitations of this study:

- Only one grade of asphalt binder was tested. Test results at stiffness levels required for SHRP compliance were consistent, however, which indicates that acceptable results can be obtained when properly sized disks are assembled. This is possible because the stiffness levels in the specification are the same for all grades.
- The gauge was restricted to circular dimensions because of a lack of data reduction schemes for other shapes, which are available from other sources in rigidity ranges that would be useful to this project.
- Data reduction was performed using procedures developed from elastic analysis, extended by correspondence principles to cal-

culate viscoelastic material properties. A viscoelastic-based study should be conducted to verify the suitability of these procedures.

- An accurate way to obtain DART rigidity values should be investigated.

Toward the end of this study, efforts were initiated to overcome some of these limitations. Initial investigations revealed some new PZT materials that exhibit significantly higher sensitivity than those used in this study. Use of such materials in assembling DART gauges will improve the accuracy of tank asphalt testing. However, because the gauges were not circular, it was not possible to use them in conjunction with the data reduction schemes available in this study. A new duomorph assembly, in which the stainless steel shim is replaced with an epoxy layer, was obtained, albeit too late for this project. This assembly possesses the stiffness and rigidity to function at elevated temperatures for tank asphalt testing and will be evaluated for suitability.

Further development using a viscoelastic finite element approach is necessary to develop data reduction schemes for any given gauge geometry, eliminating the elastic assumptions in early development, which may contain an inherent error that has not been investigated. Finite element analysis also will help validate the analytical approach employed here, help realize the full potential of duomorph technology in asphalt rheological testing, and help confirm the sample size assumptions for asphalt containers based on elastic analysis. A thorough viscoelastic analysis could facilitate a significantly reduced sample size with appropriate dimensional controls.

IMPLEMENTATION

Potential Implementation Applications

The ability of the DART to replicate SHRP binder specification testing indicates that this technology can provide data comparable with that obtained using SHRP devices for field QC/QA investigations without requiring individual pieces of equipment. It is necessary to produce a device devoted to SHRP testing of asphalt stiffness, which is fixed at each processing stage and does not vary from sample to sample. Only the temperature is allowed to vary. A properly matched DART testing could be used immediately to test asphalt binders.

Several matched duomorph pieces are required in a DART testing set. Each piece will be used for a specific testing sequence: (*a*) original and RTFOT, (*b*) PAV intermediate temperatures, and (*c*) BBR low temperatures. The DART can be sent directly to a hot-mix asphalt concrete plant to conduct tests on asphalt to indicate compliance of original material with SHRP specifications.

The DART is ideally suited for testing asphalt binders, which may be produced by a contractor through the blending of different binders. The DART can efficiently function as a QC/QA test, providing continual comparison of field samples with DART or DSR data collected on the approved blended binder during initial certification testing. On-site blending is done often (e.g., for the production of polymer modified binders). The blended material can be accepted as produced by the supplier with SHRP equipment and examined continually in the field by the DART. At the plant, where polymer is blended in line, samples can be taken at specified intervals and tested with the DART immediately once temperature stability is obtained. Differences in the DART G^* and phase angle will immediately indicate the degree of blending compliance by comparing them with the values obtained from the approved laboratory blend.

Future Implementation Research Needs

The DART testing process provides unique approaches to asphalt rheological testing, but SHRP asphalt processing requires a long time to prepare RTFOT and PAV samples (more than 24 hours). A large sample size is required, but it is not beyond normal processing procedures. Overcoming these restrictions will advance SHRP equipment testing as well as the DART testing program.

During the assembly and evaluation of the electronic equipment and DART devices, several observations about DART performance were made. These observations provide insight into the use and future study of DART assemblies. Many of these observations require further investigation before their potential is realized. Some of this research is beyond the nature of an NCHRP-IDEA Phase II study, but will interest other organizations, such as the FHWA, TRB, AASHTO, state transportation departments, and NCHRP programs, in particular the upcoming NCHRP 9-10 study, which will investigate the appropriateness of SHRP testing for modified binders.

The potential exists to perform a complete SHRP characterization on tank asphalt binders using the DART to determine *G** and phase angles from -30 °C to 60°C, with a frequency sweep at each temperature. This would provide an accurate fingerprint of the asphalt binder in a short time, which could be established when initial SHRP certification is done at the laboratory. As each tanker of asphalt cement is delivered, the fingerprint test sequence could be conducted quickly using the DART at the plant. Original SHRP aging research supports this type of testing. Aging research findings indicate that RTFOT and PAV processing merely shift the response curves from rheological testing. Different asphalts with different aging characteristics have diff-erent fingerprints. Validating this process to determine SHRP compliance will eliminate the time-consuming 24-hour process for complete SHRP field verification. SHRP testing, however, could still be performed when necessary. Extensive validation testing would be required to implement this.

Because the DART provides *G** and phase angle values, even at the extremely low temperatures required for BBR testing, the potential exists for these rheological parameters to be used to classify binders at the low temperatures predicted for the pavement instead of at a pseudo-temperature adjusted upward by 10 °C simply to allow the selected equipment to be used. The BBR could be replaced, given the accuracy provided by the DART at these lower temperatures.

The direct tension test (DDT) is fraught with problems and has not been approved. The DDT, however, probably is vital, especially for modified binders, because the BBR test does not discriminate between relevant low-temperature behavior of binders and different levels of ductility. The inability of the DTT to provide accurate, repeatable test values is a severe problem. The DART can provide *G** and phase angle values at low temperatures required by the DTT, not a pseudo-temperature selected to match the deficient BBR test equipment. The ability to obtain a phase angle at these temperatures provides a direct replacement for the strain at failure. The phase angle is the prime indicator of the balance between viscous and elastic behavior and, as such, provides an accurate indication of the ductile nature of the binder at extremely low temperatures. Research is needed to demonstrate that the characterization provided by the *G** and phase angle is better than that provided by the strain at failure, because strain already has been implanted as the necessary value. It makes no sense to conduct different specification values and tests at different temperatures. The DART may provide consistency across all temperatures.

Sophisticated viscoelastic modeling is required to reduce sample size using molds into which asphalt could be poured, coating the DART disk to a specific thickness. The DART would operate in the same manner, but would use different equations or nomographs that reflect the properties of the uniform coating on the disk instead of complete embedment. This viscoelastic modeling also will be necessary to validate the nomographs and to produce nomographs precisely calculated for the asphalt binder testing geometries of the DARTs for SHRP compliance.

The potential exists to remove the strain gauges and use the PZT voltages produced by deflecting disks instead of using the strain gauge signal. This requires slightly different signal processing because output voltage is proportional to input voltage and the rate at which the disk is being deformed. Integration of the rate-sensitive output voltage will provide a value directly proportional to the deflection of the disk. If this is consistent across all frequencies and input voltages, the strain gauges can be eliminated, and signal processing or software modifications can be used to provide the same data, resulting in an even more durable device requiring less electronic equipment.

REFERENCES

1. *SHRP-A-37: Binder Characterization and Evaluation. Volume 4: Test Methods.* Transportation Research Board, National Research Council, Washington, D.C., 1994.
2. Briar, H.P., and K. W. Bills. *Development of an In Situ Transmitter for Solid Rocket Propellant Surveillance.* Report AFRPL-TR-72-93, 1972.
3. Briar, H.P., K.W. Bills, and R.A. Schapery. *Design and Test of the Operational In Situ Gauge for Solid Rocket Propellant Surveillance.* Report AFRPL-TR-76-36, 1976.
4. Boggess, N.L., and G. Swift. *Development of Pavement Evaluation Equipment Final Report: Phase II.* Report FHWA/RD-80-009. FHWA, U.S. Department of Transportation, 1980.
5. Breeding, S.K., and D. Lavoie. Duomorph Sensing for Laboratory Measurement of Shear Modulus. *Proc, Oceans '88*, Baltimore, MD,

1988.

6. Lavoie, D., S.R. Griffin, and F.B. Grosz. DIAS—A Novel Technique for Measuring In Situ Shear Modulus. Personal communication, 1994.
7. Grosz, F.B. DUONOMO and DUO_CALC: Computer Programs for Duomorph Data Reduction. Personal communication, 1995.
8. LabVIEW Instrumentation Software. Englewood Cliffs, N. J.: Prentice Hall.