Measurement of *G** in Fine Asphalt Mixes

Dynamic Mechanical Analyzer Shear Test Implementation

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This study characterized the mechanical properties in fine asphalt mixtures by means of a microscale test. The method involved the design of the fine asphalt matrix, the specimen preparation, the performance of shear tests, and the construction of complex shear modulus master curves based on the obtained results. The tests were performed with a device called a dynamic mechanical analyzer (DMA). The test configuration consisted of a temperature and frequency sweep for a given strain level, within the linear viscoelastic range of the material. The test implementation experimental design involved the use of two aggregate sources and three asphalt types (neat, styrene–butadiene rubber modified, and ethylene copolymer modified). On the basis of the results for the mixes, master curves were calibrated by sigmoidal, Christensen–Anderson, and Christensen–Anderson–Marasteanu general models and using Arrhenius and William–Landel–Ferry shift factors. As part of the study, the DMA test based on shear loading mode was successfully implemented and allowed for measurement of a fundamental material property: complex shear modulus (*G). The *G** estimation involved measurement of shear stress, strain, and phase angles. Complex shear moduli in the range of 40 to 170 MPa were obtained; the fine asphalt mixtures modified with ethylene block copolymer developed higher stiffness, and the ones with neat binder had lower stiffness. From the *G** results, master curves were developed. A higher fit was obtained when the general sigmoidal formula was used; this result indicated the high degree of similitude in behavior between the fine asphalt matrix and the complete hot-mix asphalt mixtures.**

The complexity in behavior of the asphalt binder because of its viscoelastic properties (variability in temperature, loading time, and age) results in a broad research spectrum for the material. The following study corresponds to a characterization approach to one component of the asphalt mixture: the fine asphalt matrix.

With the purpose of performing research on the behavior of asphalt mixtures at reduced scales, LanammeUCR acquired a commercial testing device called a dynamic mechanical analyzer (DMA), which allows for the measurement of the static and dynamic response of viscoelastic materials. Although prior DMA analysis has been performed in asphalt binders and fine aggregate mixtures, by using a dynamic shear rheometer or other testing devices, dynamic mechanical analysis under different loading modes in asphalt materials is not widespread. Moreover, before this study, no testing methodology had been proposed for analyzing asphalt mixtures using the equipment acquired by LanammeUCR.

The importance of this study is that it allowed for the implementation and standardization of the use of a specific DMA tool for characterizing fine asphalt mixtures within the linear viscoelastic range of the material. Three fundamental reasons for the importance of understanding this component of the asphalt mixture are as follows: (*a*) microcracking of the asphalt mixture initiates at the fine asphalt matrix and then reflects to the surface of the pavement structure, (*b*) it is the most homogeneous component of the asphalt mixture, and (*c*) the characterization of the fine matrix allows prediction of the behavior of the asphalt mixture (*1*).

Furthermore, the study serves as an input for research on moisture damage, defined as a loss in adhesivity and durability, caused by the presence of water at the asphalt–aggregate interface or within the asphalt matrix (*2*), a typical phenomenon in Costa Rica. The following methodology allows researchers to perform micromechanical analysis of moisture damage and generate knowledge that can further improve the understanding of the mechanisms associated with this type of distress.

BACKGROUND

The micromechanical analysis of asphalt mixtures has been researched by the Texas Transportation Institute (*2, 3*), where several projects to measure the surface energy of different aggregates and asphalt sources have been performed. However, the previous research also led to the understanding of the moisture damage process, based on analysis of the micromechanisms that affect the adhesive interface between the aggregate and the asphalt and the cohesiveness and durability of the asphalt matrix. The research was performed in two distinct phases.

The first phase looked at evaluating surface energy and dynamic response of the material (*2*). The micromechanical tests that were performed are based on the application of a cyclic torsion stress at controlled strain conditions. Testing focused on the measurement of accumulated damage in the asphalt binder and the fine asphalt mixture. The results were used for quantifying the energy dissipated by the material and the energy associated with the viscoelastic deformation (*2*).

The second phase introduced the concept of energy ratio that was used to combine the energies of the adhesive and cohesive bond, as a parameter to evaluate the compatibility between asphalt binders and aggregates with respect to resistance to moisture damage (*3*). A system for the evaluation of moisture damage was developed for this purpose. The system involves studying the compatibility of an asphalt

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and aggregate source by means of surface energy and energy ratio, followed by the dynamic mechanical analysis of the fine asphalt mixture. Finally, evaluation of the moisture susceptibility of the asphalt mixture was assessed to evaluate the optimality of the mixture design and volumetric requirements for the hot-mix asphalt (HMA).

Because the previous studies demonstrated the efficiency of micromechanical analysis to assess the resistance of the fine asphalt mixture to moisture damage and fatigue cracking, a study to develop a simplified method for the material and a software tool for data analysis (fracture mechanics parameters associated with fatigue cracking and moisture damage–related parameters) was conducted (*4*). A project to implement the methodology for DMA specimen preparation was concluded in which different asphalt and aggregate materials were used. The researchers devised a method to design fine asphalt mixtures based on the actual asphalt content that is used by the fine portion of the gradation, in a given asphalt mixture (material passing the No. 16 sieve).

More recently, research to analyze the linear and nonlinear viscoelastic behavior of bituminous mortars was performed to characterize the behavior of the asphalt matrix at various temperatures and shear stress levels (*5*). The methodology implemented as part of the study maintains the same approach developed previously by the Texas A&M Transportation Institute. The research highlights the importance of performing nonlinear analysis to obtain the true behavior of asphalt mixtures in response to low-frequency loading at higher temperatures.

Other studies have also looked at different topics at the microscale level, such as the anisotropic analysis of stiffness reduction in asphalt mixtures based on micromechanical analysis (*6*). On the basis of the study, it was found that the asphalt mixture stiffness is 30% higher in the horizontal axis when compared with the vertical axis. The results were possible by studying the properties of the materials at the microscale level where the homogeneity of the material is higher, as compared with the more heterogeneous asphalt mixture.

Additionally, fine mixtures have been implemented in research on the use of recycled asphalt pavement (RAP). In this sense, a project to evaluate the properties of RAP, mixture design, and HMA mixtures with high RAP contents has been performed (*7*). The author highlights that the characterization of the RAP binder corresponds to one of the fundamental steps in the design of HMA mixtures with higher RAP contents. The material characterization was performed by means of DMA analysis. As previously mentioned, micromechanical analysis of the components of a pavement structure allows the mechanical characterization of the asphalt mixture in a practical, economic, and efficient manner.

OBJECTIVE

The project was designed with the objective of implementing a DMA testing method that allowed for the micromechanical characterization of six different fine asphalt mixtures by measuring a fundamental material property, G^*. The specific objectives of the study required the definition of a fine asphalt mixture design method based on the experimental design (two aggregate sources and three asphalt types). An experimental method for measuring the mechanical response of the fine asphalt mixture based on the DMA was developed. Finally, based on the experimental results, master curves for G^* were generated by using the sigmoidal, CA (Christensen–Anderson), and CAM (Christensen–Anderson–Marasteanu) general formulas and Arrhenius and WLF (William–Landel–Ferry) shift factors.

MATERIALS USED IN THE STUDY

As part of the study, two aggregate sources of common use in Costa Rica were selected. Based on typical project gradations for these sources and HMA mixture design, the fine portion of the gradation (material passing the No. 50 sieve) was determined. Both mixtures correspond to dense-graded mixtures of 12.5-mm and 19.1-mm nominal maximum aggregate size, henceforth referred to as Plant 1 and Plant 2, respectively.

In the case of the asphalt binders, three conditions of a unique source were selected: neat condition (PG 64-22), 1.5% styrene–butadiene rubber, and 1.5% ethylene copolymer. The modifier content was selected on the basis of the workability of the asphalt mixtures and the typical dosage that is used in the country. In both cases, the modifier was incorporated by means of high shear at 165°C for a period that varied between 3 and 4 hours (until visually the mixture was considered homogenous).

EQUIPMENT DESCRIPTION

The dynamic mechanical analysis is a technique developed to measure the viscoelastic response of materials by means of static or dynamic loading. In this regard, the DMA device that was used differs from more traditional testing where only the elastic response is evaluated and therefore only an incomplete response of the material is obtained when inelastic and viscous behavior exists. The ranges used in DMA analysis can be selected in the linear viscoelastic range of the material, to ensure that the analysis is more sensitive to the true material response.

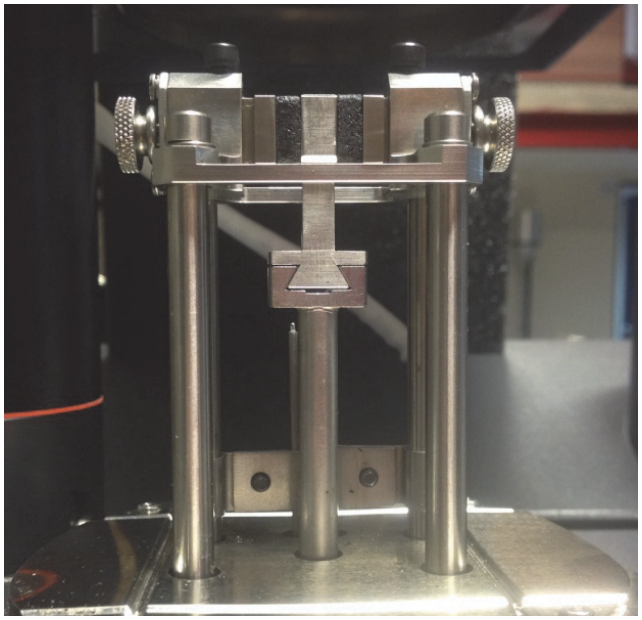
Dynamic loading tests based on the DMA are the most common and consist of the application of a sinusoidal stress or strain and the phase lag between the two factors. Based on the DMA Q800 equipment, parameters such as storage modulus, loss modulus, loss and storage compliance, phase angle, complex shear modulus, dynamic or complex viscosity, stress, relaxation modulus, dynamic or static load, temperature, time, frequency, displacement, and stiffness can be measured.

For the current research project, the shear loading mode test was implemented. As part of the test setup, two samples of equal dimensions and material properties are placed between two fixed supports. Between the two samples, a metal plate is used for generating shear (Figure 1). This testing mode is ideal for materials such as gels, adhesives, resins, and other high-viscosity compounds (*8*). With respect to the loading mode, the samples to be evaluated can have a maximum dimension of 10 mm in length and width and 4 mm in thickness.

According to the test configuration shown in Figure 1, the stress is applied on the face of the specimens; therefore, it is necessary to ensure that the samples have 100% contact with the clamps. Since the sample consists of two specimens, both were taken from the same batch to ensure homogeneity.

The specimens were attached to the faces of the moveable clamp, thus ensuring that there is no displacement. Before the test is started, the sample is subjected to pure shear stress, which is kept constant until the load with the controlled strain is applied.

The implementation of shear testing in torsion will be accounted for in future studies to correlate with dynamic shear rheometer results. The study is intended to establish the testing conditions for the DMA apparatus under a specific loading mode, including the adhesion between the fine asphalt mixture and the metal plate.



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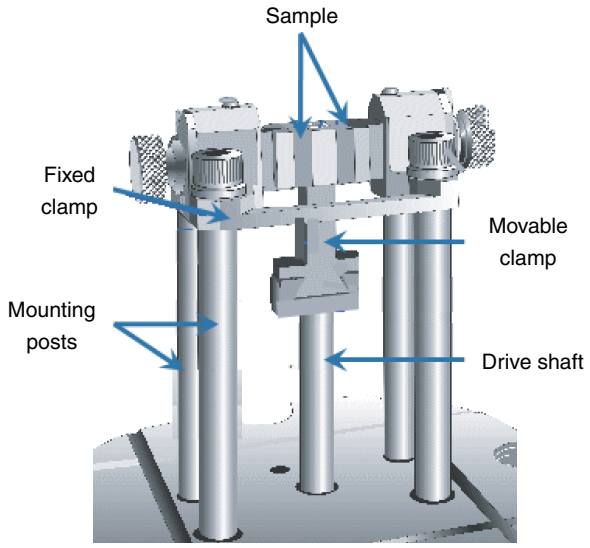

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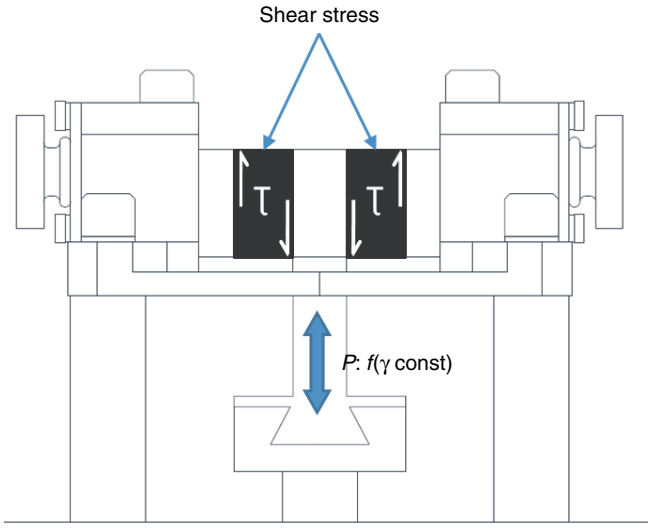

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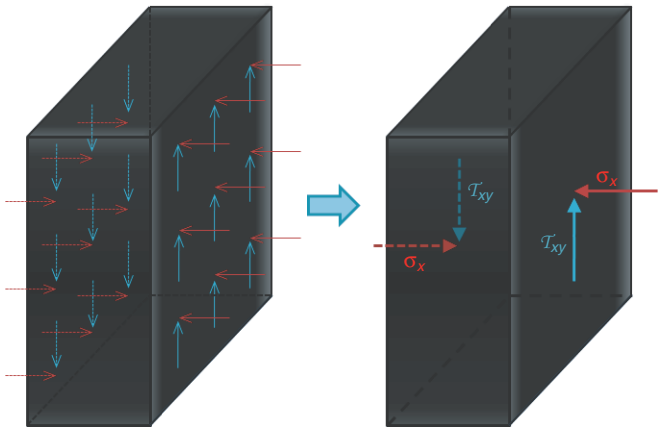

(d)

FIGURE 1 DMA shear test equipment configuration: (*a*) shear clamp, (*b*) parts of shear clamp and DMA chamber, (*c*) load mode, and (*d*) stress state of each specimen [$P = f(\gamma \text{ const})$ = load P is function of controlled angular strain γ; σ_x = normal stress; T_{xy} = shear stress].

FINE ASPHALT MATRIX DESIGN

The estimation of the asphalt content for the fine asphalt matrix required for DMA testing is based on the methodology proposed by Howson et al. (*3*). The methodology consists of calculating the thickness of the asphalt film that coats the granular material particles, as a function of gradation, asphalt content of the HMA, and properties of the asphalt binder. There are currently more accurate techniques to estimate the asphalt content (*4*); however, because of the size of the aggregate particles (passing No. 50 sieve), it is not possible to apply them.

Table 1 shows the asphalt contents that were required by the fine asphalt mixture for the six experimental conditions that were tested in the laboratory.

TABLE 1 Mixture Types Evaluated by Means of DMA

Fine Asphalt Matrix	Aggregate Source	Asphalt Type	Asphalt Content[a] (%)
1	Plant 1	Neat binder	17.30
2	Plant 2	Neat binder	15.15
3	Plant 1	Neat binder + 1.5% SBR	17.30
4	Plant 2	Neat binder + 1.5% SBR	15.15
5	Plant 1	Neat binder + 1.5% EC	17.30
6	Plant 2	Neat binder + 1.5% EC	15.15

NOTE: SBR = styrene–butadiene rubber; EC = ethylene copolymer.
[a]Percentage of binder that coats material passing No. 50 sieve, with respect to asphalt content in HMA design.

DESIGN AND PREPARATION OF DMA SAMPLES

For the DMA sample preparation, molds based on the equipment specifications were designed according to the maximum dimensions that can be accommodated by the testing apparatus. The designed molds consist of metallic sections that are clamped together by means of screws, so that the retrieval of the samples is a simple process.

The mixing and molding process considers several concepts introduced by Loría for characterizing asphalt mortars (*7*). The implemented methodology uses a three-step procedure, in which the first step consists of the material preparation phase: temperature of aggregate and asphalt binder is raised to 150°C (mixing temperature).

The second phase corresponds to the mixing process, which was based on the methodology proposed by Loría to prepare asphalt mortar (*7*). A small metallic container is placed over a Bunsen burner and the materials are added and mixed until a homogeneous mixture can be observed. The maximum mixing time could not exceed 1 min.

The third phase corresponds to the specimen molding process. The molds are heated to the mixing temperature to ensure that the fine asphalt matrix temperature does not drop at a high rate, because of a significant temperature differential, resulting in poor compaction. The molds are greased with a petroleum-based lubricant before mixture placement. After the mixture is placed in the molds, uniform pressure is applied on the top face of the specimen by means of a spatula. Finally, the samples are removed from the molds and placed over a rigid layer to avoid any deflection in the material. The samples are placed in a zero-humidity chamber at room temperature until ready for testing. Figure 2 shows this process.

Validation of the sample preparation procedure was performed by means of scanning electron microscopy at the sample surface. Figure 3 shows some of the obtained results. The images allowed for visual monitoring of the surface voids and verification of the randomness in their distribution. Furthermore, the samples were checked for homogeneity in all sample faces and the possibility of failure planes (none were observed). After this process, the samples were deemed suitable for testing or discarded.

TEST METHOD DESCRIPTION

The type of test that was used to evaluate the DMA samples in shear mode was a strain-controlled multifrequency analysis. The frequencies used in the testing procedure were 0.1, 0.5, 1, 5, 10, and 25 Hz, at the following temperatures: –10°C, 4.4°C, 21.1°C, 37.8°C, and 54.5°C. The testing parameters are identical to those specified for HMA dynamic modulus testing according to AASHTO TP 62.

The strain level was selected to ensure that the sample remained within the linear viscoelastic range for the test temperatures. A strain sweep was performed to determine an appropriate strain level. Figure 4*a* shows that for strain values above 0.01%, the material begins to accumulate damage because the material performs outside of the linear range. Finally, on the basis of the strain sweep test and the observed variability, a strain level of 0.01% was selected.

Figure 4*b* shows a typical test output at different temperature and frequency conditions. On the basis of the test setup, the testing time is 112 min, which accounts for five 12-min periods required to adjust temperature and stabilize the environmental chamber. The figure shows the expected decrease in modulus associated with temperature increases and frequency reductions.

(a)

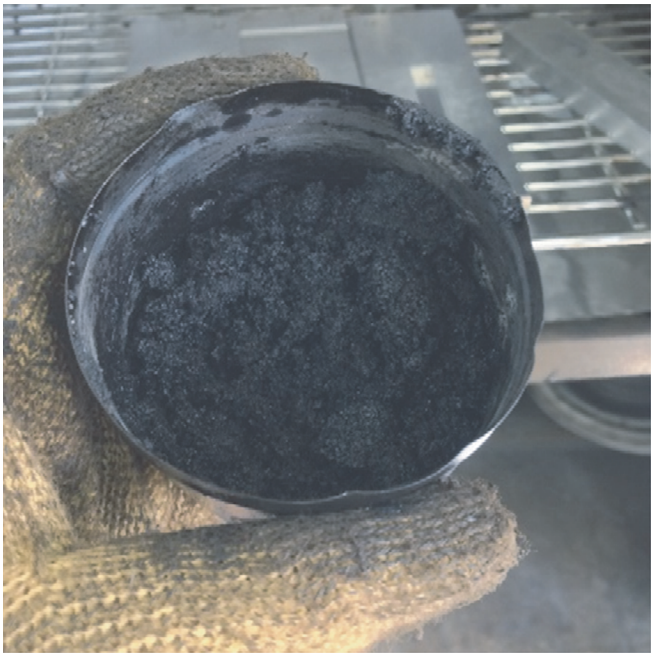

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FIGURE 2 Sample preparation.
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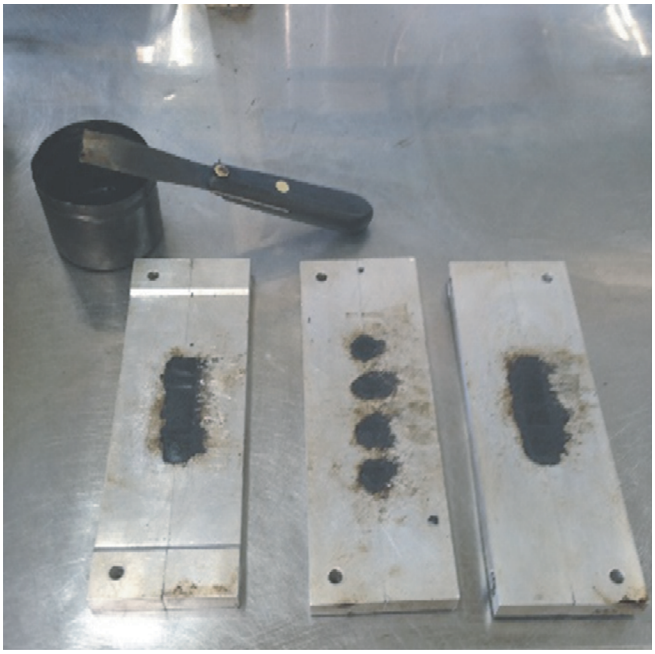

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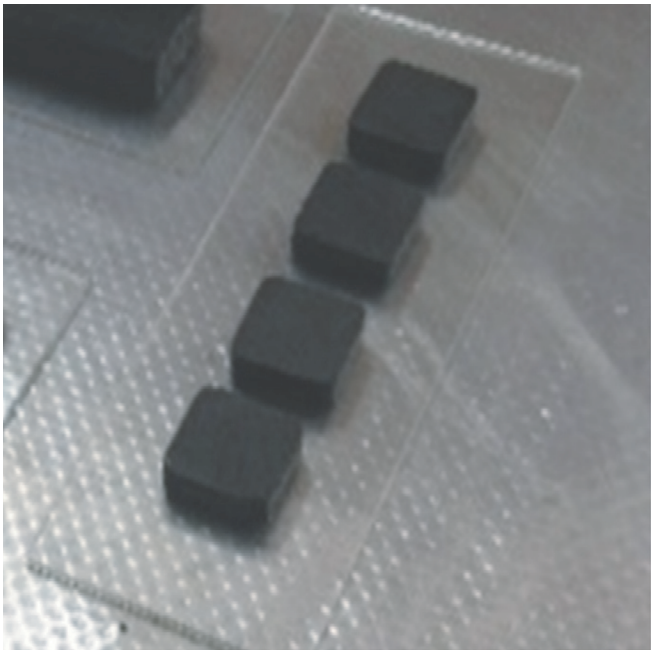


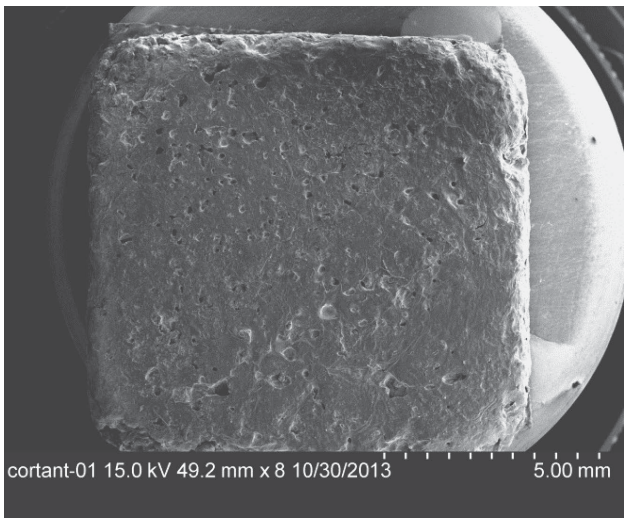
(d)

FIGURE 2 *(continued)* Sample preparation.

The selection of the required number of testing replicas was determined by means of a statistical procedure similar to Monte Carlo simulation. The process consisted of recording the variation results based on monitoring of the mean and standard deviations of the measured response and randomly combining different samples for given sample sizes (n). Consequently, a total of 120 random combinations of three to seven replicates were evaluated. Figure 5 shows the variability of the standard deviation of the measured properties for different sample sizes.

The least efficient sample size (higher variability) occurred for a sample size of $n = 4$: higher data spread (thicker distribution tails). For a sample size of $n = 5$ and $n = 6$, the spread of the data was similar. Consequently, a sample size of $n = 5$ was considered optimal to ensure repeatability in test results.

Once the required sample size was defined, a sensitivity analysis of the results was performed to account for the error caused by the heterogeneity involved in specimen preparation. The analysis was based on the Mellin transformation, which applies to functions that



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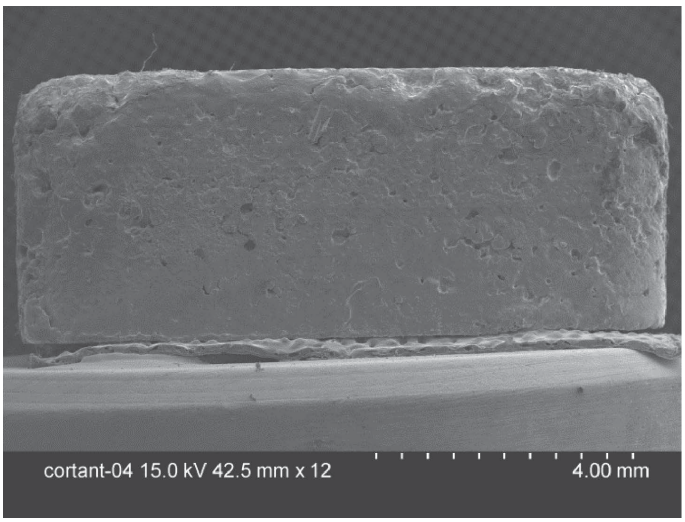
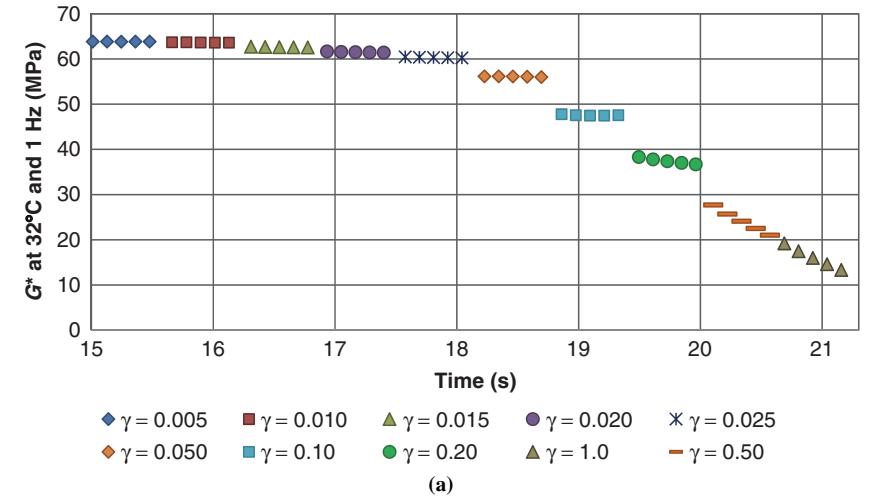


(b)

FIGURE 3 Scanning electron microscopy images of DMA sample surface.



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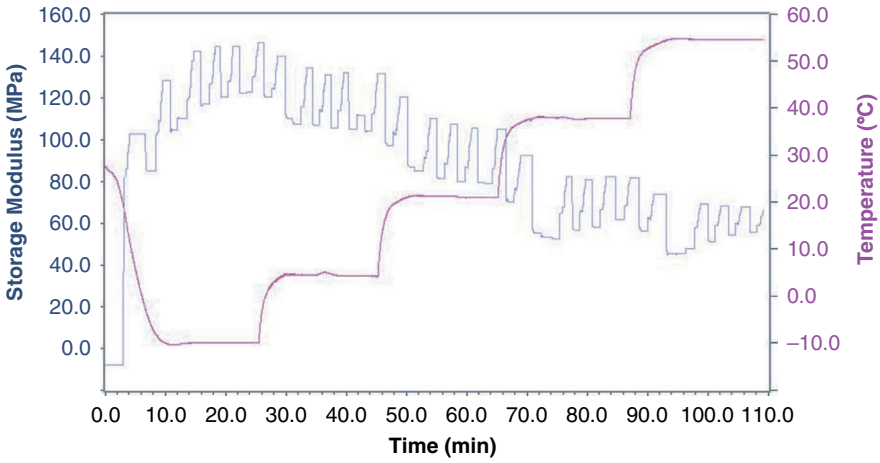


(b)

FIGURE 4 DMA results: (*a*) strain sweep test and (*b*) strain-controlled multifrequency shear test.

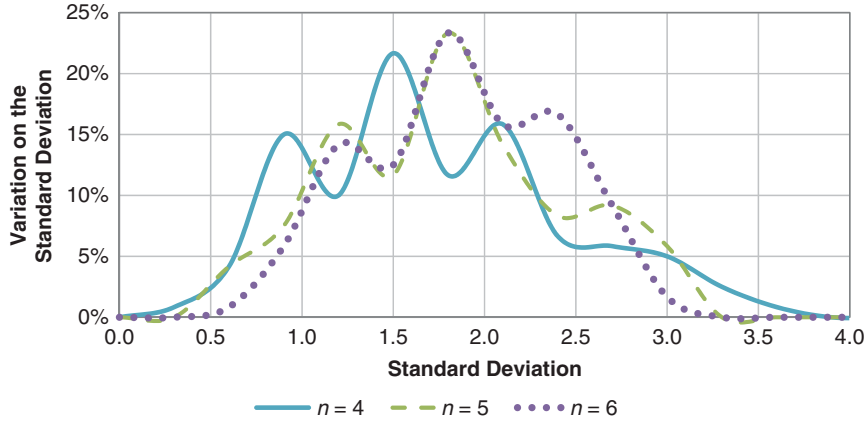


FIGURE 5 Variability of standard deviation of measured properties for varying sample sizes.

are defined for positive numbers only, as is the case of the elastic component of shear modulus. With this uncertainty analysis, the most probable variability of the modulus was estimated, after considering the intrinsic heterogeneity related to the parameters that are involved in the estimation of the modulus: specimen dimensions and sample stiffness.

The Mellin transformation considers the probabilistic distribution of the independent variables of the modulus and assigns to each a transformation function. The most likely variability is calculated on the basis of the product of the individual Mellin transformation functions for each independent factor (*9*). With the use of these criteria, the modulus can be expressed as

$$G' = \frac{3\,Kt}{5\,w} \tag{1}$$

$$M_{G'} = \left(\frac{3}{5}\right)^{s-1} M_K(s)\,M_t(s)\,M_w(2-s)\,M_h(2-s) \tag{2}$$

where

G' = storage modulus,
K = stiffness,
t = thickness,
w = width,
h = length,
$M_{G'}$ = Mellin transformation for modulus,
M_K = Mellin transformation for stiffness,
M_t = Mellin transformation for thickness,
M_w = Mellin transformation for width,
M_h = Mellin transformation for length, and
s = gamma function related to Mellin transformation for normal variables.

The transformed functions are then evaluated in models for the probability distribution of each factor. Each parameter was subjected to statistical goodness-of-fit tests to determine the most likely population distribution. The tests evaluated fit on the basis of a normal distribution, lognormal distribution, and Weibull distribution. Finally, according to the previous analysis it was estimated that the most probable standard deviation for the storage modulus is 0.6 MPa. Furthermore, because the viscous component for the shear complex modulus as measured by the DMA is in the range of an order of magnitude below that of the elastic component, it is realistic to assume that an uncertainty for the storage modulus is expected in the complex modulus value.

ANALYSIS AND RESULTS

The individual shear tests were analyzed to verify the variability of the samples. Figure 6 shows the relationship between dynamic modulus and frequency at different temperatures in linear and logarithmic scales, as well as the Black Space diagram and the Cole–Cole plot for a specific sample. For verification of the validity of the G^* measurements, the linearity and parallel tendency of the isotherm curves were analyzed (Figure 6, *a* and *b*, corresponding to a typical sample).

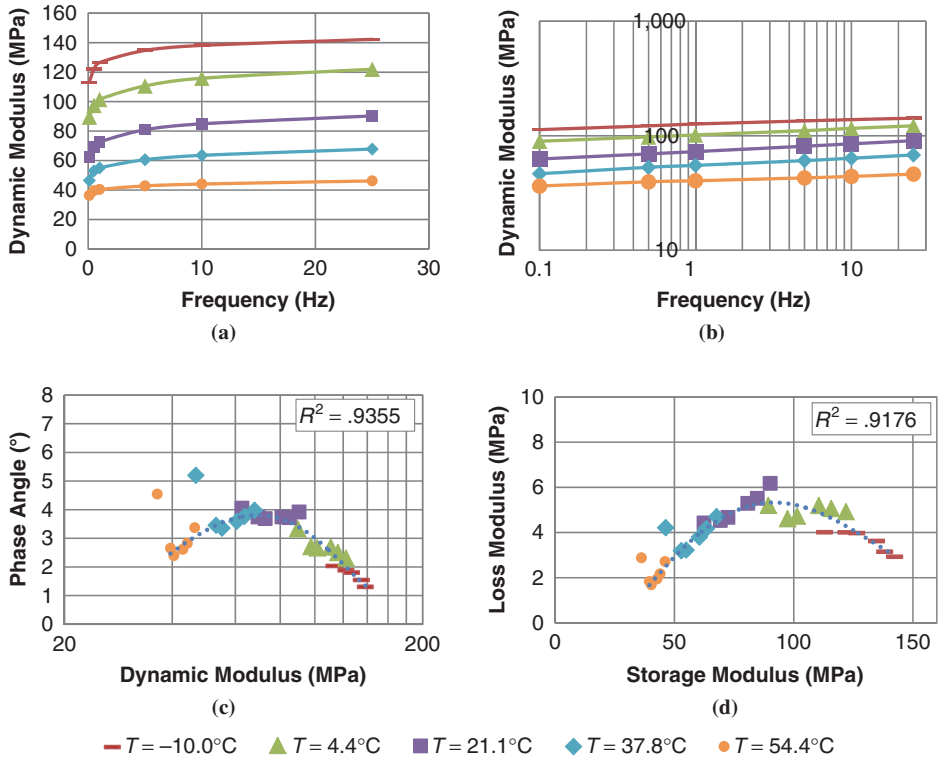


FIGURE 6 Testing for sample of fine asphalt mixture: (*a* and *b*) isotherms, (*c*) Black Space diagram, and (*d*) Cole–Cole plot.

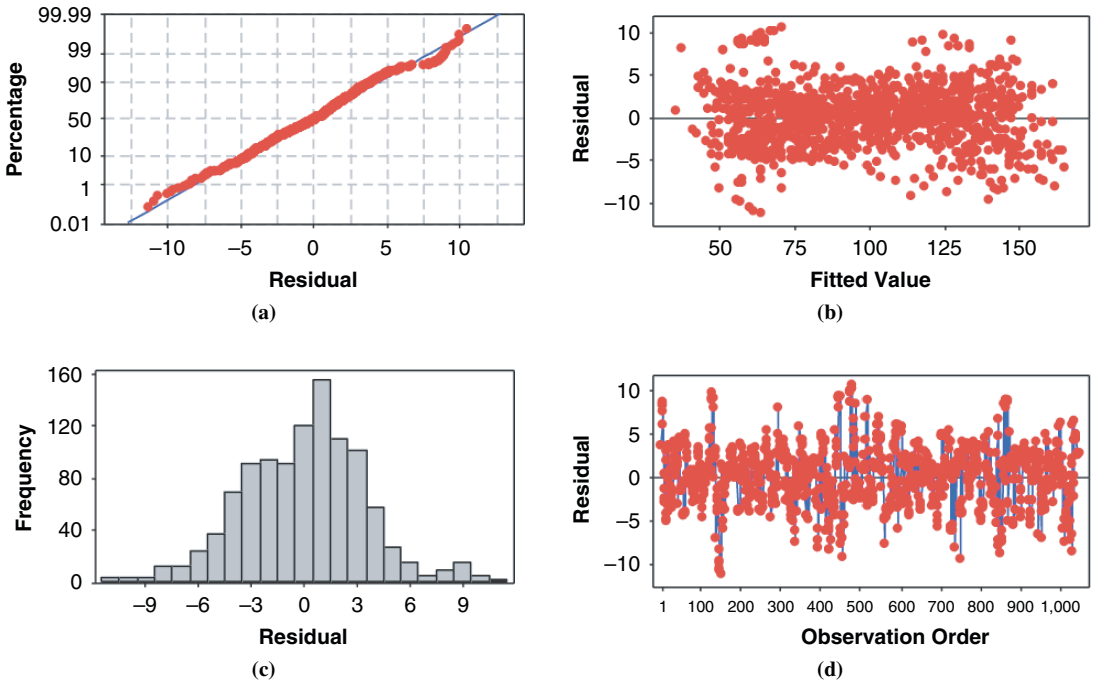


FIGURE 7 Residual plots for G^* from normal distribution goodness-of-fit test: (*a*) normal probability, (*b*) residual versus fit, (*c*) histogram, and (*d*) residual versus order.

The results were submitted to a normal distribution goodness-of-fit test, as shown in Figure 7. In the case of a general linear model for G^* versus temperature, frequency, and a volumetric parameter of the mix, adequate correlation was obtained: R^2 of 98.80% and adjusted R^2 of 98.73%.

The Black Space diagram (Figure 6*c*) provides information on the material behavior and suggests whether the fine asphalt matrix behaves as an asphalt binder or as an asphalt mixture. The hypothesis assumes that for an asphalt binder the phase angle increases as temperature increases, while for asphalt mixes the phase angle increases with temperature up to a given point and then drops (*10*). The obtained results indicate an increase in the phase angle from −10°C up to 21.1°C and a decrease from 37.8°C onward, indicating a response similar to that of an asphalt mixture.

The Cole–Cole plot (Figure 6*d*) allows material analysis at low and intermediate temperatures (*10*). Adequate fit in the plot translates to a thermorheological simple material and consequently justifies the application of time–temperature superposition (thermorheological simplicity is dependent and strongly correlated to the bitumen composition). Higher correlations were observed when the neat binders were compared with the modified asphalt binders.

Coefficients of variation (CVs) for all mixtures were obtained and in all cases showed values below 15%. As expected, lower CVs were associated with lower temperatures and high frequencies, whereas higher CV values related to higher temperatures and low frequencies. Consequently, several observations at 0.1 Hz and 54.5°C had to be discarded because of high variability. Finally, considering a typical variability associated with rheological tests of 20%, the quality of the data was acceptable.

On the basis of the DMA shear test results, the parameters for a mechanical model were calibrated to evaluate the test results for the fundamental properties of the asphalt binder and the asphalt mixture. The calibrated model represents the 2S2P1D model (abbreviation for two springs, two parabolic creep-type elements, and one dashpot model), based on the generalization of the Huet–Sayegh model. Table 2 shows the calibrated model parameters for the six analyzed fine asphalt mixtures. The h, k, G_∞, G_0, and η are parameters associated with two parabolic creep elements, two springs, and a dashpot, respectively (Table 2). (The parameter η does not appear in Table 2 because $\eta = (E_\infty - E_0)\beta\tau$ and is calculated before model calibration.)

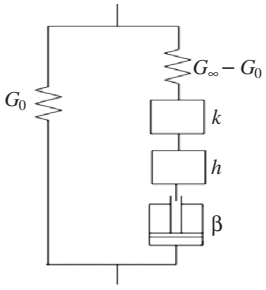
As shown in the table, k-values in the range of 0.16 to 0.19 were obtained, while h-values ranged between 0.43 and 0.68; this result indicates an increase in the k-value with respect to an increase in mixture stiffness. The fine asphalt matrices containing neat binders, and lower stiffness than their modified counterparts, are associated with the lowest β-values. This finding is expected since the parameter is directly related to binder stiffness. Furthermore, because of the thermorheological complex behavior, the α-parameter serves as an indicator of testing accuracy. In the current study, higher α-values were found with the mixtures containing modified asphalt binders (*11*). In general, the goodness-of-fit indicators in the calibrated models are high with R^2 values above 99% and the standard error of predicted values divided by the standard deviation of measured values (S_e/S_y) relationship below 0.09 for all cases (*12*).

MASTER CURVE ESTIMATION

Master curves for all fine asphalt mixtures using the general sigmoidal, CA, and CAM model equations, and applying the Arrhenius and WLF shift factors (Figure 8), were developed. Figure 8 shows a fine asphalt mixture master curve calibrated with the general sigmoidal,

TABLE 2 2S2P1D Model Parameters

Parameter	Value, by Fine Asphalt Mixture						2S2P1D Model
	1	2	3	4	5	6	
G_∞ (MPa)	162.953	154.709	163.428	178.923	164.414	169.861	
G_0 (MPa)	46.374	50.184	48.991	52.148	50.106	58.544	
k	0.17	0.19	0.19	0.16	0.19	0.17	
h	0.48	0.43	0.51	0.5	0.68	0.62	
α	3.45	3.71	7.94	2.98	8.5	3.12	
β	798	729	202	222	202	209	
τ	12.61	10.61	777.73	6.4	902.19	12.8	
S_e/S_y	0.046	0.049	0.088	0.075	0.087	0.079	
R^2	.998	.998	.994	.996	.995	.996	



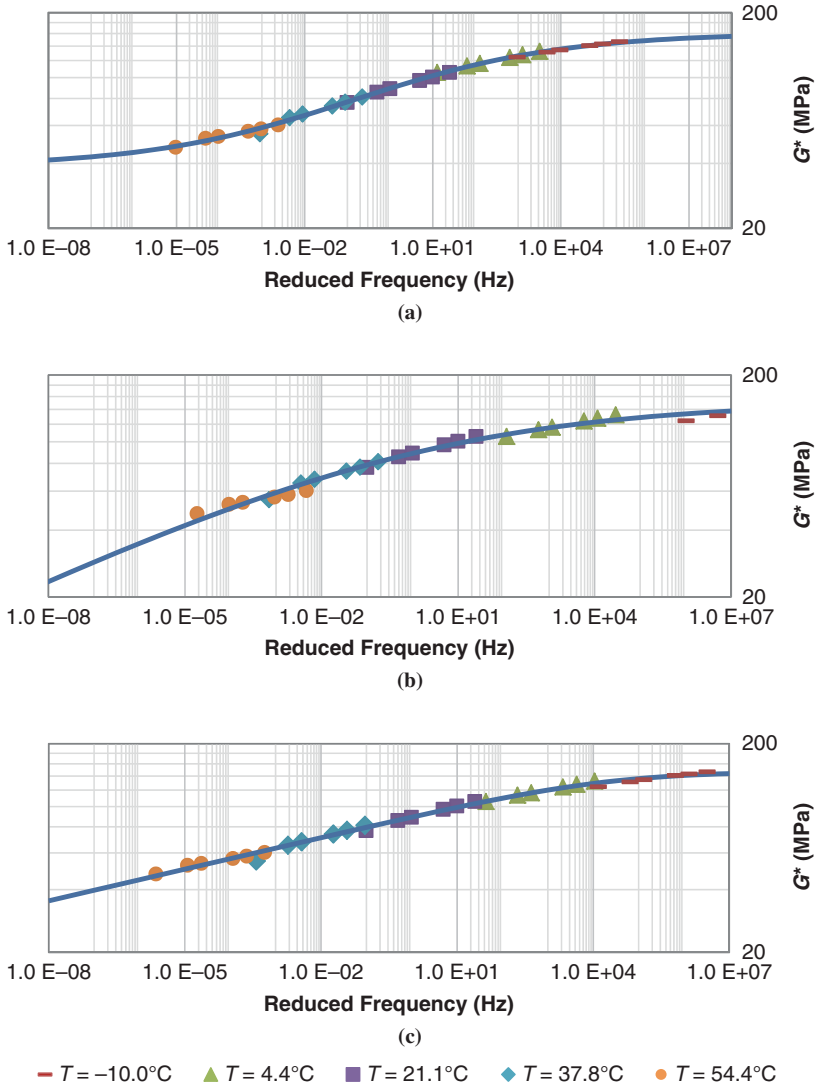


FIGURE 8 Master curves using WLF shift factors with (*a*) sigmoidal model, (*b*) CA model, and (*c*) CAM model.

CA, and CAM models and WLF shift factors. According to the results, the sigmoidal function provided the best fit for all evaluated fine asphalt mixtures. Figure 8*a* shows a smooth *S*-curve, with a S_e/S_y ratio below 0.05, and R^2 of 99% with an associated error of 0.2%.

In general, all master curves calibrated with the general sigmoidal model showed an excellent fit regardless of the selected shift factor (R^2 values between 97% and 99%). The previous observation corroborates the conclusion of the Black Space diagram; this result indicated that the fine asphalt matrices show behavior similar to that of the asphalt mixture.

In the case of the master curves calibrated with the CA model (Figure 8*b*), high R^2 values were also identified ($R^2 > 92\%$ with 1% errors). As for the master curves estimated by using the CAM model, linear trends were observed (Figure 8c), and consequently the model is not considered appropriate for the data.

On the basis of the fit with the different models, significant differences were identified in the predicted tails. As observed, the predicted modulus of the fine asphalt matrices is relatively low because of the stiffness of the fine aggregate mineral structure in comparison with that of the complete gradation. Furthermore, the high asphalt binder content of the fine asphalt matrix results in lower stability and higher flexibility.

The analyzed material showed behavior that is similar to that of conventional asphalt mixtures. However, the former tend to develop stiffness in the order of 1×10^{10} Pa, while the results measured with the DMA tests on the fine asphalt mixtures resulted in moduli in the order of 1×10^{8} Pa. Consequently, the fine asphalt mixtures exhibit intermediate modulus values between those observed in asphalt mixtures and those in the asphalt binder, presenting a difficulty in the master curve construction.

Generally, linear viscoelastic behavior occurs between the glassy transition state (in the case of asphalt materials, it starts at –20°C). In the case of the evaluated fine asphalt mixtures, the glassy transition starts at –10°C (Figure 8*a*). Additionally, the Newtonian liquid state can be expected to occur above 54.4°C (Figure 8*a*). In general, asphalt binders show this transition at approximately 70°C. These material properties can be associated with low-temperature cracking and rutting, respectively.

A comparison between the observed modulus for the six different fine asphalt mixtures was performed. On the basis of the aggregate source, no significant differences in the material modulus were observed. However, based on the binder type, stiffness differences ranged from 3% at low temperatures to 18% at high temperatures. Figure 9 shows the *G** values for the different binders at 4.4°C; the error bars represent a typical error of 5%. The higher stiffness values are associated with the fine asphalt mixtures using ethylene copolymer modified asphalt.

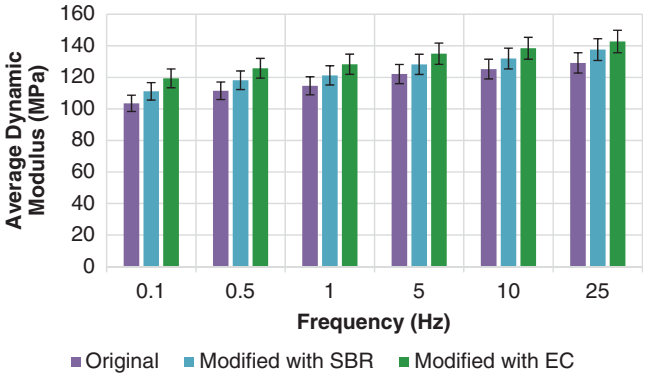


FIGURE 9 *G** comparison for fine asphalt mixtures at 4.4°C.

SUMMARY AND CONCLUSIONS

The implementation of a DMA test under shear loading mode allowed for laboratory characterization of fine asphalt mixtures based on the material response to dynamic shear loads. The following are the main findings of the research project:

- DMA complex shear modulus values based on the testing configuration ranged from 40 to 170 MPa, with the higher stiffness in modified asphalt binders.
- The material behavior of the fine asphalt mixtures resembles that of the asphalt mixtures, on the basis of the phase angle behavior observed on the Black Space diagram.
- A sensitivity analysis indicated that the most probable standard deviation associated with the complex modulus, on the basis of the uncertainty of testing parameters such as sample dimensions and material heterogeneity, is about 0.60 MPa. The previous finding implies that 97.5% of all measurements can have an associated error between 0.5% and 3% caused by sample preparation and material heterogeneity.
- Because the analyzed material mostly behaves as a thermorheological stable material, the sigmoidal general model resulted in the best fit for master curve development, with fine asphalt matrix stiffness values between those of the asphalt mixture and those expected of the asphalt binder.
- No significant differences in material response were identified for the fine asphalt mixtures using asphalt binder modified with styrene–butadiene rubber and ethylene copolymer at 1.5% concentrations.

As a result of the experience developed as part of the project and the success in implementing the DMA testing methodology, further research is recommended to validate the results obtained with the proposed method. Finally, the effects associated with changes in the sample geometry, loading ranges, and subsequently loading modes need to be further researched. Toward this goal, testing based on compression, tension, and bending modes is currently being implemented.

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