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Publication date
2019

Document Version
Accepted author manuscript

Published in
Proceedings of 2019 TRB Annual Meeting

Citation (APA)
Zegard, A., Smal, L., Naus, R., Apostolidis, P., Liu, X., van de Ven, M., Erkens, S., & Scarpas, A. (2019). Field Trials with Epoxy Asphalt for Surfacing Layers: Province of North Holland Case Study. In *Proceedings of 2019 TRB Annual Meeting: 13-17 Januari 2019, Washington, USA* Transportation Research Board (TRB).

Field Trials with Epoxy Asphalt for Surfacing Layers
Province of North Holland Case Study

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Submitted for presentation and publication for the 98th meeting of the Transportation Research Board.

Abstract: For many years, epoxy modification has become a promising solution to improve the durability of asphalt paving materials offering the potential to develop long-lasting surfacing on steel orthotropic bridge decks and other applications. In this study, an epoxy-based modifier named epoxy asphalt consisting of two-components (i.e., an epoxy resin and an acid-type hardening agent in bitumen) is used in combination with two different asphalt binders. In the first stage of this study, a decision framework is developed to select the asphalt binder for in-field use. Laboratory tests on the epoxy modified binders were conducted in a dynamic shear rheometer to evaluate their fatigue performance. The modified asphalt binders were tested at the three aging levels (virgin, RTFOT-aged and PAV-aged) and the linear amplitude sweep results have demonstrated performance differences when different binders were used. In the second stage of the current study and based on the laboratory testing results, the epoxy modified asphalt binder of the highest fatigue life was chosen for in-plant and in-field trials. Two case studies on the use of epoxy-based modifier in an asphalt wearing surface mix are reported within an effort to optimize the production, delivering and construction phases of epoxy-asphalt concrete mix.

INTRODUCTION

Epoxy modification of asphalt mixtures for surfacing layers on heavy pavement structures have gained increasing interest over the years. Nowadays, with the rapid increase in traffic volumes, the performance of pavement structures need to be improved to prevent severe defects, such as fatigue cracking. The use of epoxy-based polymeric modifiers can extend the service life of critical transportation infrastructure parts, such as bridges, tunnel and intersections (*1-7*). The scope of this study is to develop the asphalt binder that gives the highest fatigue performance in combination with an epoxy-based modifier, called epoxy asphalt (EA). The epoxy-modified asphalt with the best fatigue behaviour will be used in two field trial with surfacing layers to optimize the production, delivering and construction phases of epoxy modified-asphalt mixtures.

BACKGROUND

The implementation of EA in an asphalt binding system to increase the durability of surface pavement layers has gained increasing interest over the last years based on the good experience with the performance of EA-mixes (*1-7*). Nevertheless, EA is not a new technology, since it was developed originally by Shell Oil Company in the 1950s as a material with superior resistance to jet fuel damage (*8*). Initially, this material was applied as surface solution on heavy duty pavement structures in industrial areas with a limited number of highway applications. In 1967, EA was adopted as a thin surfacing solution on San Francisco Bay's mile-long San Mateo-Hayward Bridge, still reported to be in excellent service conditions for almost 50 years. From that time, this technology has been used on a number of major bridges around the world (*9*).

In recent years, successful trials of epoxy-modified materials have been carried out on various trial sections in all over the world (*4*) demonstrating encouraging indications for the longevity of these structures. However, due to the thermo-hardening nature of EA (*10-12*), special care is needed to ensure full mixing of all the components at the time of in-plant production and to prevent over-curing during the material transport/delivery and in-field operations (i.e., paving and compaction). Therefore, the past experience of manufacturing pavement structures should be taken into account for any further development.

Fatty acid-type epoxy-modified mixes were studied at lab-scale and were applied successfully in-field with a continuous mixing plant at a temperature range between 100 and 130^{o}C (typical warm-mix production temperatures). Despite some difficulties encountered with the in-plant production and material delivery of EA mixes mainly because of the uncontrolled curing characteristics of the EA type (amine-type) used, the implementation of a fatty acid-type EA solved this problem, resulting in very satisfying applications in New Zealand (NZ) (*4*). From these field trials, it was suggested to use an automated distribution system to blend automatically the incorporating parts of EA into the conventional mixing system. The possibility of cleaning the plant by blowing compressed air and special cleaning agents (e.g. kerosene) after the completion of the operations was recommended as well. Special attention should be given to the storage tank, pumping systems, and transport lines involved with the in-plant production.

Overall, the continuous production and construction was preferred to avoid interruptions in the whole manufacturing cycle, despite the high initial cost for controlling precisely the procedures. It is believed that the high initial cost can be counteracted by the increased productivity and the reduced compaction problems, and ultimately a high quality end-product. The modification of asphalt binder with EA can increase the service life of pavements (i.e., four to six times longer service life than with unmodified materials) compared to the high initial cost of modifier (i.e., about three times) (*4*) and, hence, this development has been accepted as attractive technology. Considering the increasing demand to guarantee the durability of pavement materials, the binder modification with epoxy technologies in critical transportation infrastructure applications (*5-7*) is becoming a very interesting option.

MOTIVATION AND OBJECTIVES

In this study, the EA was used as modifier into the asphaltic material to generate an economically feasible end-product with improved performance and longer service life. It is known that the incorporation of EA as modifier in asphalt concrete mixes improves the resistance to moisture- and oxygen-induced damage. However, limited information is available about the fatigue resistance of EA modified binders specially designed for binders in pavement structures. In order to select the best binder for fatigue, a decision framework was developed. The selected modified binder based on the lab-scale test results was used in the constructed asphalt pavements. Especially, linear amplitude sweep (LAS) tests showed the importance of selecting the best performing epoxy modified binder for fatigue. After the selection of the epoxy-asphalt binder, the mixture for a thin surface layer was produced in-plant, transported to the job site, paced and compacted. Special attention was given to the timing of the various manufacturing phases to minimize any risk related to accelerated curing of the developed materials. As mentioned before, due to the thermosetting nature of the EA mixes, these materials need close monitoring during the mixing production, transport and laying in order to achieve the highest quality.

MATERIALS

The EA, here named epoxy modifier, was supplied by ChemCo Systems Ltd, California, USA and is a two-phase chemical system solvent-free; (i) the Part A (epoxy resin formed from epichlorhydrin and bisphenol-A) and (ii) Part B (fatty acid hardening agent in 70 pengrade bitumen) (**Fig. 1**). Two types of 70-100 pengrade asphalt binders were epoxy modified to select the binder for modification with the highest fatigue life for the field trials later on. These local binders were modified at a weight ratio of 25:75 of epoxy binder and local asphalt binder. All the samples were prepared by mixing first Part B and Part A with weight ratio of 80:20, according to the supplier. Unless otherwise stated the two parts of modifier were oven-heated separately for 1 hour, to 85^{o}C (Part A) and 110^{o}C (Part B). Then, they are mixed together for approximately 10 to 20 seconds to produce the epoxy modifier (EA) and was EA was then diluted with the already pre-heated local bitumen at 120^{o}C. All the samples were placed in a refrigerator at -10^{o}C to prevent any further reaction.

Afterwards, the studied modified binders were exposed to aging in the rolling thin film oven test (RTFOT) at 163^{o}C and 1.0 atmosphere for 85 min (AASHTO T 240). Also, these binders with 3-mm film thickness were aged on pressure-aging vessel (PAV) pans with a diameter of 140-mm and aged at 2.1-MPa pressure and 100^{o}C for 48 hrs (AASHTO MP1) as well. The rheological properties were measured by conducting frequency sweep tests using a dynamic shear rheometer (DSR, Anton Paar, EC Twist 502) at a strain amplitude of 0.1% to prevent any damage. The frequency sweep tests were performed to obtain the linear viscoelastic parameters (i.e., complex modulus and phase angle) of undamaged binders to be used as a fingerprint test. The data generated in this test were also used for the evaluation of the fatigue life of these binders. The testing temperatures ranged from -10 to 50^{o}C. The standard parallel plate testing geometries were used to evaluate the viscoelastic properties of the different modified binders. Plates of 8-mm diameter with a 2-mm sample gap were used at temperatures below of 20^{o}C, while at a temperature above 30^{o}C plates of 25-mm diameter with a 1-mm sample gap were used. The properties were measured at frequencies of 0.1-10 Hz. The samples of base binders were treated in the same way and master curves were constructed at a reference temperature of 30°C.

Fig. 2(a) shows master curves of complex modulus and phase angle for the epoxy modified asphalt binder A (EA-A) at the three aging intervals (virgin, RTFOT-aged and PAV-aged). As shown, there is a slight difference in the measured complex shear modulus data after aging. At lower frequencies (i.e. in-field high temperatures), EA-A shows a stiffening effect while at higher frequencies (i.e., in-field low temperatures) the stiffness decreases after aging. This result indicates an increase in deformation resistance at high temperatures and crack resistance at low temperatures. The comparison of PAV-aged data of the base asphalt binders A and B (A-A and A-B), and epoxy modified asphalt binders A and B (EA-A and EA-B) is given in **Fig. 2(b)**. A visible difference in the results of A-A and EA-A can be seen while A-B and EA-B does not show visible difference in the results. This indicates that not every binder is suitable for modification.

LAS TESTING FOR FATIGUE LIFE PREDICTION

Due to the fact that the best performing binder will be determined based on their long-term performance, in this part a decision framework is developed for the material selection at lab-scale to use it as binding element for the constructed pavements later on. Especially, the fatigue in pavement structures is caused by the accumulated damage resulting from repeated traffic loading. For this reason, based on the PG specifications (*13*, *14*), used for some contracts in the Netherlands as well, standard tests are conducted to explore the asphalt binder fatigue resistance under a given environmental and traffic loading situation (i.e., one temperature and strain level under repeated loading cycles). However, apart from the fact that the fatigue resistance varies with the temperature (*15*), standard testing will be an expensive method for pavement designers and contractors and a considerable amount of effort should be spent in the laboratory to precisely evaluate the fatigue of binders. Therefore, the LAS testing method could be the answer for quick enough decision making.

The LAS testing method has been proposed as alternative to the current specifications to allow the practitioners to design structures faster and efficiently based on an oscillatory strain amplitude sweep test that can induce accelerated damage. The standard DSR testing configuration at lower temperatures (i.e., the standard 8-mm parallel plate geometry with a 2-mm gap) is used for LAS experiments (AASHTO TP 101). In particular, the strain amplitude is increasing incrementally generating material damage in the binder at a constant frequency of 10 Hz. According to the LAS testing protocol, the definition of damage is the degradation of material integrity under repeated loading. An initial 100 cycles of sinusoidal loading at 0.1% applied strain level is used to obtain the undamaged viscoelastic properties. Each successive loading step consists of 100 cycles at a rate of increase of 1% applied strain per step for 30 steps, beginning at 1% and finishing at 30% applied strain. The accelerated procedure of the LAS testing requires the rheological parameters obtained in the previously described frequency sweep tests which were used as model input for the undamaged, linear viscoelastic response of the investigated binders.

In this study, the assessment of the fatigue resistance of asphalt binders will be considered at 10 and 20^{o}C, temperatures at which the possibility of edge flow will be limited (*16-18*). Thus, the instable flow will be prevented, and the cohesive radial cracks will propagate from the sample testing periphery toward the centre of the sample demonstrating more precise results about the failure mechanism of material. Similarly, the load amplitude was selected within the range of 0.01 to 10 MPa to, avoid confounding effects of edge flow or adhesion damage. The damaged parameters were obtained following the LAS method which is linear oscillatory strain sweep with strain amplitudes ranging from 0.1 to 30% (*19*). Due to the presence of material or geometric non-linearity, and for simplification purposes, the shear stress and strain mentioned here are apparent shear stress and strain at the sample edge. They are calculated based on a linear radial decrease to the center in relation to the total torque.

Performance Prediction with S-VECD Model

In the past, the viscoelastic continuum damage (VECD) model (*20, 21*) was developed based on Schapery's work potential theory for damage growth (*22*) and by implementing this model the output from LAS tests was used to analyse the complex fatigue behaviour of asphaltic materials (*23*). The primary benefit of using VECD was that results from a single test run at a specific set of conditions can be used to predict the behaviour of that material under any variety of conditions. Herein, the simplified viscoelastic continuum damage (S-VECD) model was implemented to LAS test results to enable the fatigue life prediction at any strain amplitude including a failure criterion.

This model utilizes an internal state variable to represent damage (*D*) because of microstructural changes that lead to the loss of material integrity (*C*), otherwise pseudo stiffness. Especially, the relationship between damage and material integrity at any time (t) can be derived from the work potential theory and is calculated as shown in equation 1:

$$D(t) \cong \sum_{i=1}^{N} [\pi {\gamma_0}^2 (C_{i-1} - C_i)]^{\frac{\alpha}{\alpha+1}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}} \quad (1)$$

where $C(t) = |G^*(t)|/|G^*_{initial}|$ is the material integrity; γ_0 is the applied strain for a given cycle (%); $G^*(t)$ is the complex shear modulus at time *t* (MPa) corresponding to the conditions of interest and is the fingerprint determined on the basis of the initial linear modulus in the amplitude sweep test. $G^*_{initial}$ is the initial undamaged complex shear modulus (MPa); α is material parameter constant determined from frequency sweep test data of the previous described tests; i is time steps. In this model, temperature effects have been incorporated through the use of time–temperature superposition (*24*). When reduced time and frequency are used in place of actual time and frequency, the relationship between C and D is temperature independent (*19, 24)*. Reduced time and frequency are calculated with linear viscoelastic time–temperature shift factors, and thus, the framework allows for predicting the fatigue response at any temperature of interest with fatigue test results at a single test temperature coupled with linear viscoelastic shift factors.

To incorporate the S-VECD model into fatigue life prediction, a power law model is developed to fit the material integrity versus damage curve according to Eq. 2

$$C(t) = 1 - C_1(D)^{C_2} \tag{2}$$

where C_1 and C_2 are coefficients derived from the curve-fitting. The fatigue failure point is defined as the peak shear stress which corresponds the marked change in the loss of material integrity. The damage accumulation at failure (D_f) is further calculated as

$$D_f = \left(\frac{1 - C_{peak\ stress}}{C_1}\right)^{1/C_2} \tag{3}$$

The fatigue law describing the relationship between the number of cycles to failure, or fatigue life, (N_f) and the strain amplitude (γ_{max}) can be expressed as

$$N_f = A(\gamma_{max})^{-B} \tag{4}$$

where A (=fatigue model parameter) and B (=-2α) are power law coefficients. The A fatigue model parameter defined as

$$A = \frac{f(D_f)^k}{k(\pi C_1 C_2)^\alpha} \tag{5}$$

where k is $1 + (1 - C_1)\alpha$; f is loading frequency (Hz).

As shown in Eq. 4, the damage intensity at a certain number of fatigue cycles can be calculated at any strain level, providing the opportunity to designers to adjust this level according to traffic loads of studied pavements. Thus, quick indications about the fatigue life at any strain amplitude of interest can be obtained quickly with the use of the S-VEDC model from the LAS results at a single temperature coupled with the linear viscoelastic parameters.

The apparent shear strain-stress was obtained for all binders and presented in **Fig. 3**. The virgin EA-A shows a lower yield stress in comparison to the aged EA-A (**Fig. 3a**). The virgin EA-A and EA-B show almost identical yield stress, but after aging EA-A shows a higher yield stress than EA-B (**Fig. 3b**). The effect of aging on the neat binder and the epoxy modified binder is similar (**Fig. 3c**). In addition to this, **Fig. 3c** shows clearly the effect of the epoxy modification through the increase of the yield stress of the binder. The damage and failure analysis of the S-VECD model is based on the relationship between the material integrity (*C*) and the damage intensity (*D*) (**Fig. 4**). The fitted model predicts quite good the experimental data as can be seen in **Fig. 4**.

The fatigue life of the binders is predicted with the S-VECD approach (**Fig. 5**), in which the epoxy modified binders show much higher fatigue life than the local penetration binder at both 10 and 20^{o}C. The higher fatigue life of PAV-aged epoxy modified binder indicates that the fatigue performance of modified binders improves after PAV-aging, mainly thanks to the already formed network of epoxy modifier in the asphalt binder. From the fatigue results it can be concluded that binder A improves more than binder B after epoxy modification. Therefore, the EA-A binder was selected for the plant and field trials. In these trials the mix production, transport and construction phases are investigated and the results are reported in the following sub-section.

TEST SECTION APPLICATION

A (twin axle) batch mix plant at Asfalt Productie de Eem (APE), the Netherlands, was used by Dura Vermeer to produce the epoxy-stone mastic asphalt mix (ESMA) by using the best performing binder based on laboratory studies. The gradation of ESMA is shown in **Table 1**. In general, the visual appearance of the ESMA mix was similar to an unmodified asphalt mix.

In-plant Production

In order to have complete control over the heating conditions of the liquid thermosetting parts of the modifier, an in-line temperature system and a mass flow-control automated distribution system was installed to produce these components. Part B was pre-heated at 120^{o}C and pumped from the distributor at ground level (**Fig. 6(a)**) up to the mixing pugmill of the plant. In parallel, Part A was pre-heated at 75^{o}C in its storage tank (**Fig. 6(b)**). Part A and Part B were pumped in the bitumen weighing vessel and premixing of the two components was achieved by the bitumen injection pump. After premixing, the conventional components of ESMA were added at 120^{o}C and the produced mix was discharged to trucks for transport to the trial sections. Isolated Live Bottom Belt Asphalt trucks were used for the transport of the mixture to prevent temperature segregation of the mixture entering in the paver.

In-plant Study Trial

Although this epoxy modified asphalt mixture may be handled in a similar way to normal asphalt mixtures, time and temperature are critical to the successful manufacturing of the epoxy modified material. Thus, before manufacturing the trial surfacing road for the Province of North Holland (PvNH), a 100-m field trial was constructed at the APE plant (**Fig. 7(a)**) to optimize the quality of the material via monitoring the development of mechanical properties of ESMA under controlled conditions. The development of properties demonstrates the curing profile of this specific ESMA and its optimization is important to obtain the desired reaction rate of the epoxy modification for the local conditions. A paver with vibrating/tamper screed and an three wheel static roller followed by a tandem steel wheel vibratory roller were used for paving and compaction, respectively. For the quality control testing of the prepared ESMA mix, Marshall specimens (EN 12697-34) were produced and the measured Marshall properties were used to indicate the timing for opening the pavement to traffic. The requirements were a minimum stability of 5-30 KN and a maximum flow of 4-7 mm, respectively at 60^{o}C. Based on the results from the in-plant trial section, the transport conditions for the PvNH trial, and paving and compaction procedures of the ESMA were determined by the contractor in accordance with national standards. All these procedures were similar those used for conventional SMA paving materials.

In-field Study Trial

The time between plant production and the start of construction was about 90 min. A polymer modified tack coat was applied to the prepared surface, After delivering the material, ESMA was held in the truck at 120^{o}C. Total time between mixing and finishing of compaction was approximately 4 hours. The compaction was done by a three wheel static roller (10 metric tons) followed by a tandem steel wheel vibratory roller (7.5 metric tons). The mix compaction took approximately 30 min and at the end of compaction the temperature was between 65 to 90°C, under sunny and dry weather conditions (**Fig. 7(b-c)**). As noticed also in the past (*4*), large-scale mix production resulted in slower curing rates leading subsequently to a slower development of properties than was measured at lab-scale preliminary studies. In fact the reverse was expected. However, the curing rate was high enough and thus the trial section was opened to traffic the same afternoon. Finally, the workers and any person involved in the whole manufacturing process did not experience any unusual smell or fuming. The early opening to traffic of ESMA is the subject of on-going research.

CONCLUSIONS AND RECOMMENDATIONS

The focus of this paper was to provide insight in the large-scale surfacing applications of epoxy-modified asphalt mixtures designed after dedicated laboratory studies. The main conclusions of this paper are that : (i) not all asphalt binders are suitable for epoxy modification, and (ii) the epoxy-modified overlays should be paved within a specific time frame to warrant good quality pavement layers. Based on the research reported in this paper, a time frame for production and delivery of the asphalt concrete mix was chosen, but this needs to be investigated more extensively in the future. Finally, the field trial surfacing of the road in the Province of North Holland provides useful information for future applications of epoxy-based modifiers.

ACKNOWLEDGEMENTS

This research was funded by the Province of North Holland (PvNH), the Netherlands. Laboratory tests were performed at the Dura Vermeer (DURA). The authors appreciate the support of Niels Heins for his work in DURA Laboratory. John Bors of Chemco Systems has provided valuable recommendations to the in-field operations. Their efforts are gratefully acknowledged.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: L. Smal, R. Naus, P. Apostolidis; data collection: A. Zegard; analysis and interpretation of results: L. Smal, R. Naus, P. Apostolidis, X. Liu, M.F.C. van de Ven, S. Erkens, A. Scarpas; draft manuscript preparation: P. Apostolidis, A. Zegard. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Widyatmoko, I., B. Zhao, R.C. Elliott, W.G. Lloyd. Curing Characteristics and the Performance of Epoxy Asphalts. *Presented at Tenth International Conference on Asphalt Pavements*, Quebec, Canada, 2006.
2. Herrington, P., D. Alabaster. Epoxy Modified Open-graded Porous Asphalt. *Road Materials and Pavement Design 9(3)*, 2008, pp. 481-498.
3. Luo, S., Q. Lu, Z. Qian. Performance Evaluation of Epoxy Modified Open-graded Porous Asphalt Concrete. *Construction and Building Materials 76*, 2015, pp. 97-102.
4. International Transport Forum. *Long-life Surfacings for Roads: Field Test Results*. ITF Research Reports, OECD, Paris, France, 2017.
5. Stenko, M.S., A.J. Chawalwala. Thin Polysulfide Epoxy Bridge Deck Overlays. In *Transportation Research Record: Journal of the Transportation Research Board 1749*, TRB, National Research Council, Washington, D.C., 2001, pp. 64-67.
6. Bocci, E., F. Canestrari. Analysis of Structural Compatibility at Interface between Asphalt Concrete Pavements and Orthotropic Steel Deck Surfaces. In *Transportation Research Record: Journal of the Transportation Research Board 2293*, TRB, National Research Council, Washington, D.C., 2012, pp. 1-7.
7. Yin, C., H. Zhang, Y. Pan. Cracking Mechanism and Repair Techniques of Epoxy Asphalt on Steel Bridge Deck Pavement. In *Transportation Research Record 2550*, TRB, National Research Council, Washington, D.C., 2016, pp. 123–130.
8. Simpson, W.C., H.J. Sommer, R.L. Griffin, T.K. Miles. Epoxy Asphalt Concrete for Airfield Pavements. *Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineer 86*, 1960, pp. 57–71.
9. Lu, Q., J. Bors. Alternate Uses of Epoxy Asphalt on Bridge Decks and Roadways. *Construction and Building Materials 78*, 2015, pp. 18-25.

10. Apostolidis, P., X. Liu, C. Kasbergen, M.F.C. van de Ven, G. Pipintakos, A. Scarpas. Chemo-rheological Study of Hardening of Epoxy Modified Bituminous Binders with the Finite Element Method. In *Transportation Research Record*, 2018, TRB, National Research Council, Washington, D.C.
11. Apostolidis, P., X. Liu, M.F.C. van de Ven, S. Erkens, A. Scarpas. Kinetic Viscoelasticity of Crosslinking Epoxy Asphalt. In *Transportation Research Record,* 2019, TRB, National Research Council, Washington, D.C.
12. Apostolidis, P., X. Liu, M. Zhang, M.F.C. van de Ven, S. Erkens, A. Scarpas. Chemical and Oxidative Age Hardening of Epoxy-modified Bitumen. In *Transportation Research Board Annual Meeting,* 2019, National Research Council, Washington, D.C.
13. Bahia, H.U., D.I. Hanson, M. Zeng, H. Zhai, M.A. Khatri, R.M. Anderson. *NCHRP Report 459: Characterization of Modified Asphalt Binders in Superpave Mix Design.* TRB, National Research Council, Washington, D.C., 2001.
14. Bahia, H.U., H. Zhai, M. Zeng, Y. Hu, P. Turner. Development of Binder Specification Parameters Based on Characterization of Damage Behavior. *Journal of the Association of Asphalt Paving Technologists,* Vol. 70, 2002, pp. 442–470.
15. Anderson, D.A., Y.M. Le Hir, M.O. Marasteanu, J.-P. Planche, D. Martin, and G. Gauthier. Evaluation of Fatigue Criteria for Asphalt Binders. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1766,* TRB, National Research Council, Washington, D.C., 2001, pp. 48–56.
16. Hintz, C., H.U. Bahia. Understanding Mechanisms Leading to Asphalt Binder Fatigue in the Dynamic Shear Rheometer (DSR). *Journal of the Association of Asphalt Paving Technologists,* Vol. 14, 2013, pp. 231–251.
17. Anderson, D.A., Y.M. Le Hir, M.O. Marasteanu, J.P. Planche, D. Martin, G. Gauthier. Evaluation of Fatigue Criteria for Asphalt Binders. In *Transportation Research Record, No. 1766,* Transportation Research Board of the National Academies, Washington, D.C., 2001, pp. 48-56.
18. Apostolidis, P., C. Kasbergen, A. Bhasin, A. Scarpas, S. Erkens. Study of Asphalt Binders Fatigue with a New Dynamic Shear Rheometer Geometry. In *Transportation Research Record, 2473-18,* TRB, National Research Council, Washington, D.C., 2018.
19. Hintz, C., R. Velasquez, C. Johnson, H. Bahia. Modification and Validation of Linear Amplitude Sweep Test for Binder Fatigue Specification. In *Transportation Research Record, No. 2207,* National Research Council, Washington, D.C., 2011, pp. 99–106.
20. Kutay, M.E., N.H. Gibson, J. Youtcheff. Conventional and Viscoelastic Continuum Damage (VECD)–Based Fatigue Analysis of Polymer-Modified Asphalt Pavements. *Journal of the Association of Asphalt Paving Technologists,* Vol. 77, 2008, pp. 395–434.
21. Wen, H., H. Bahia. Characterizing Fatigue of Asphalt Binders with Viscoelastic Continuum Damage Mechanics. In *Transportation Research Record, No. 2126,* National Research Council, Washington, D.C., 2009, pp. 55–62.
22. Schapery, R.A. Correspondence Principles and a Generalized J-Integral for Large Deformation and Fracture Analysis of Viscoelastic Media. *International Journal of Fracture,* Vol. 25, No. 3, 1984, pp. 195–223.
23. Hintz, C., H. Bahia. Simplification of Linear Amplitude Sweep Test and Specification Parameter. In *Transportation Research Record, No. 2370,* National Research Council, Washington, D.C., 2013, pp. 10–16.
24. Underwood, B.S., Y.R. Kim, M.N. Guddati. Characterization and Performance Prediction of ALF Mixtures Using a Viscoelastoplastic Continuum Damage Model. *Journal of Association of Asphalt Paving Technologists,* Vol. 75, 2006, pp. 577–636.

LIST OF TABLES AND FIGURES

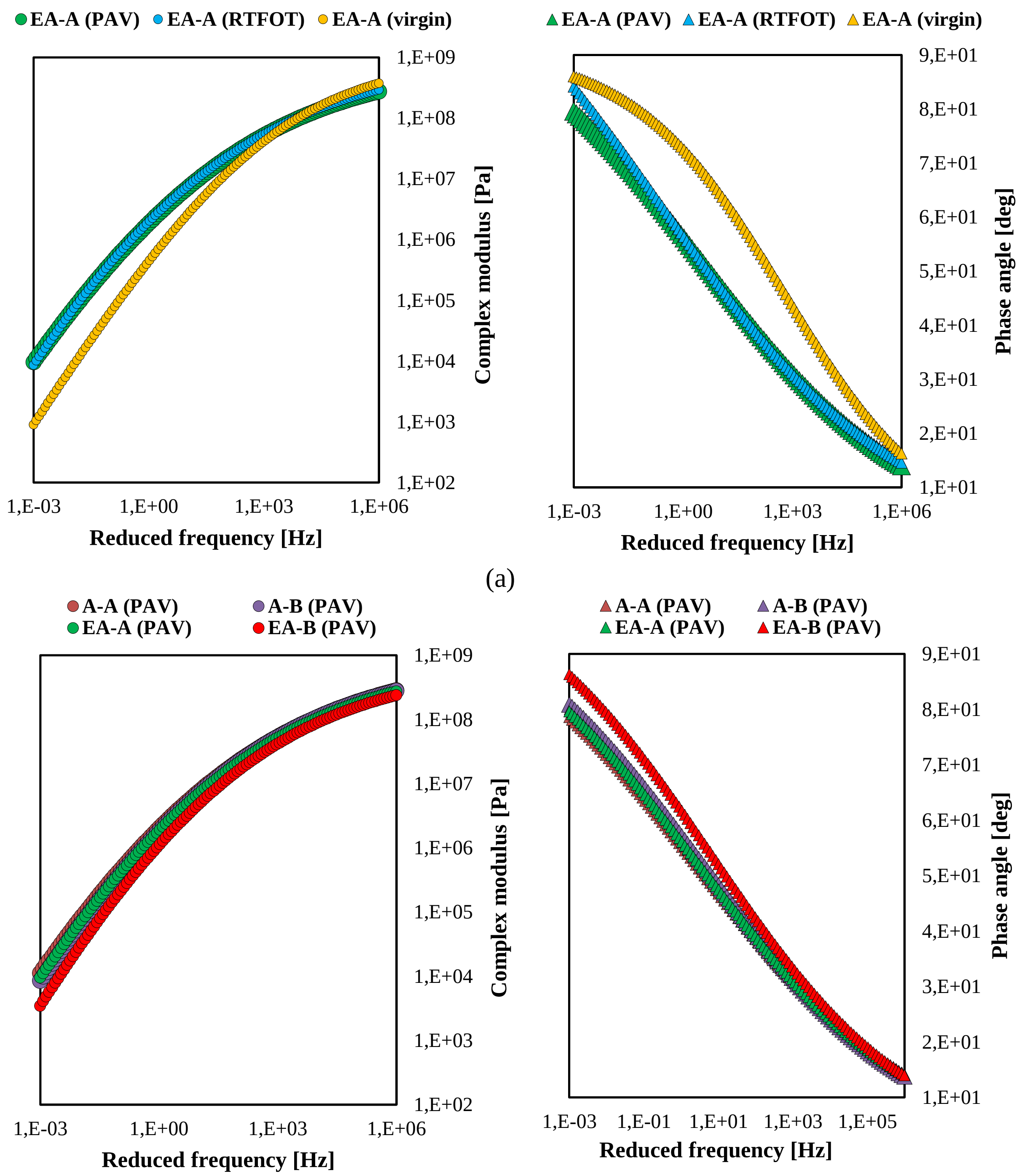
TABLE 1 ESMA mix gradation

Sieve Size (mm)	min. (% m/m)	max. (% m/m)	Percentage Passing (% m/m)
11.2	98	100	100
8	86.5	99.5	95.2
5.6	46.1	60.1	57.8
4			
2	16.9	28.9	23.1
0.5	11.1	19.1	15.9
0.063	6.2	11.2	9.8

Binder content (% m/m) : 6.7

(a) (b)

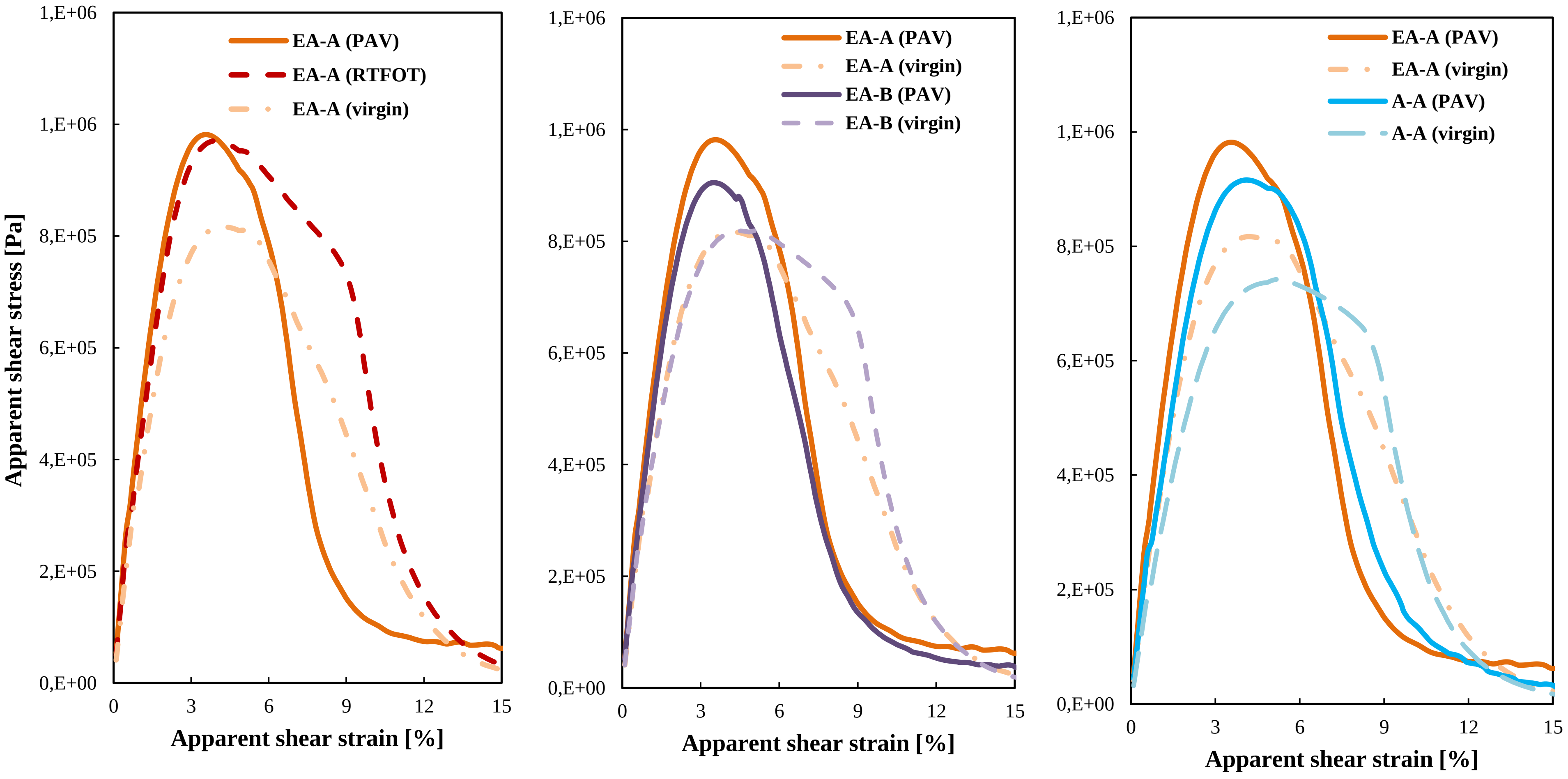
FIGURE 1 View of epoxy modifier liquid constituents: (a) Part A, and (b) Part B



(a)

(b)

FIGURE 2 Complex shear modulus (left) and phase angle (right) of (a) modified binder A after RTFOT and PAV, and (b) modified binders A and B after PAV



(a) (b) (c)

FIGURE 3 Shear stress and strain output from the LAS test for different binders at 10°C

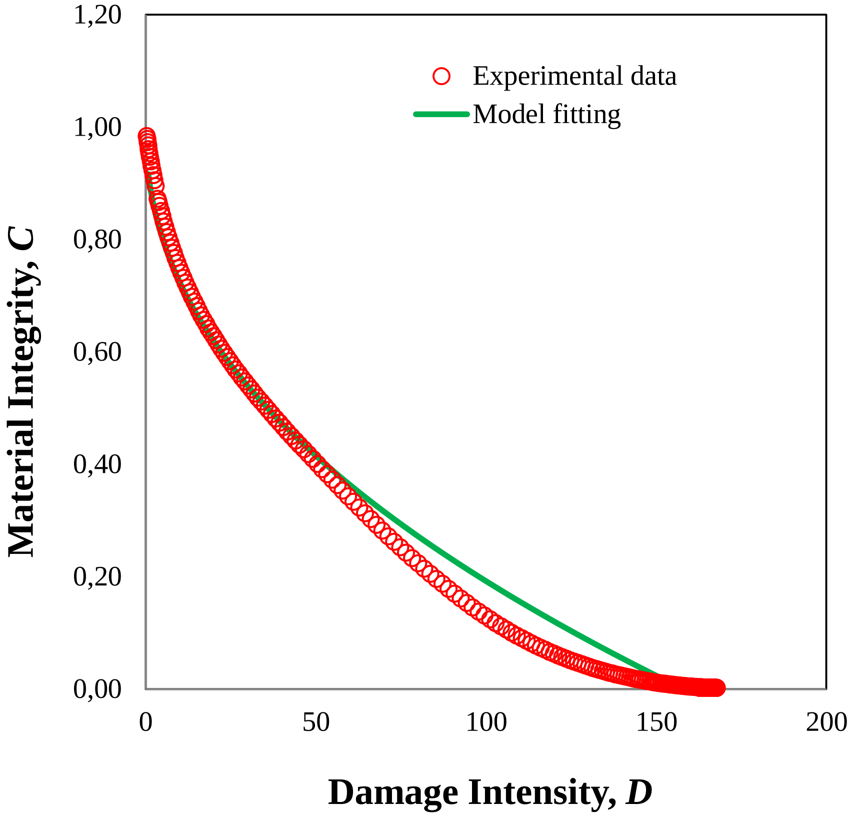
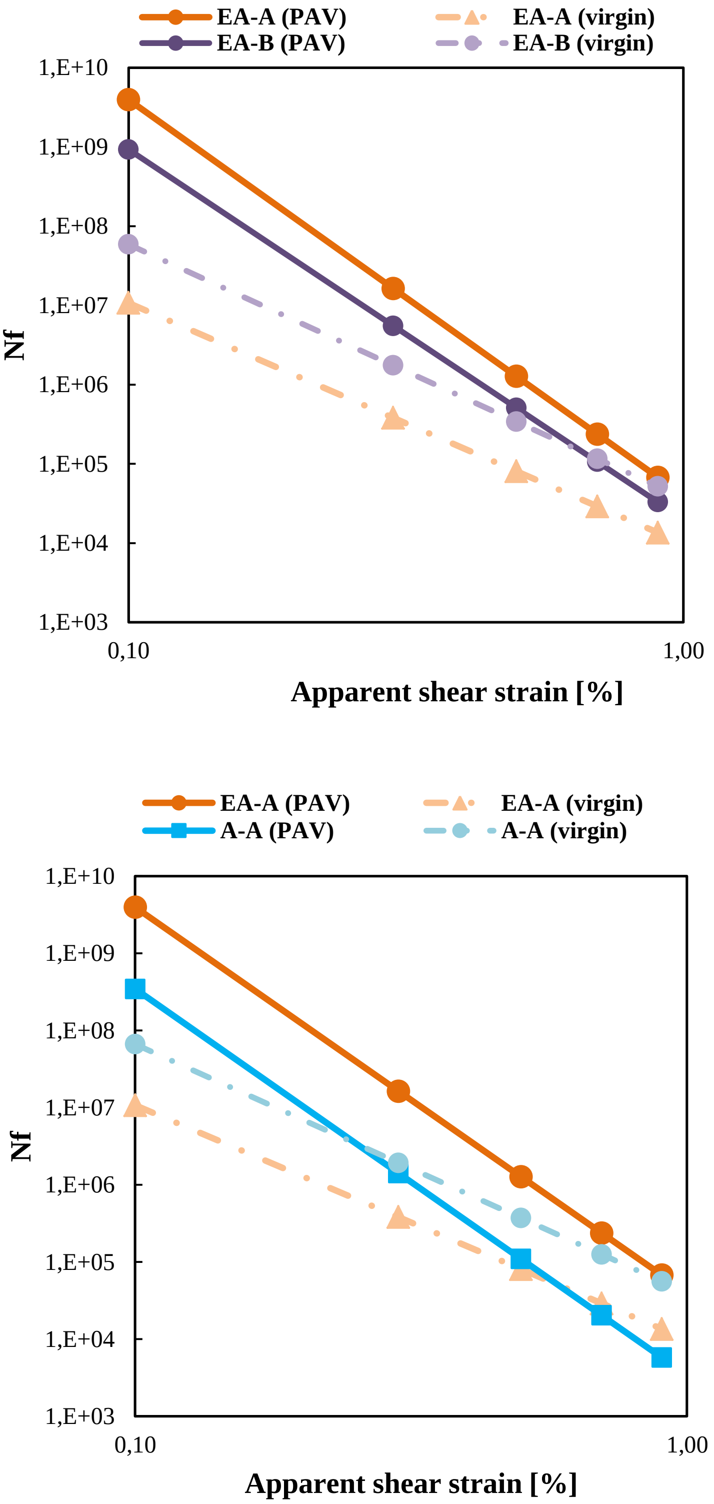
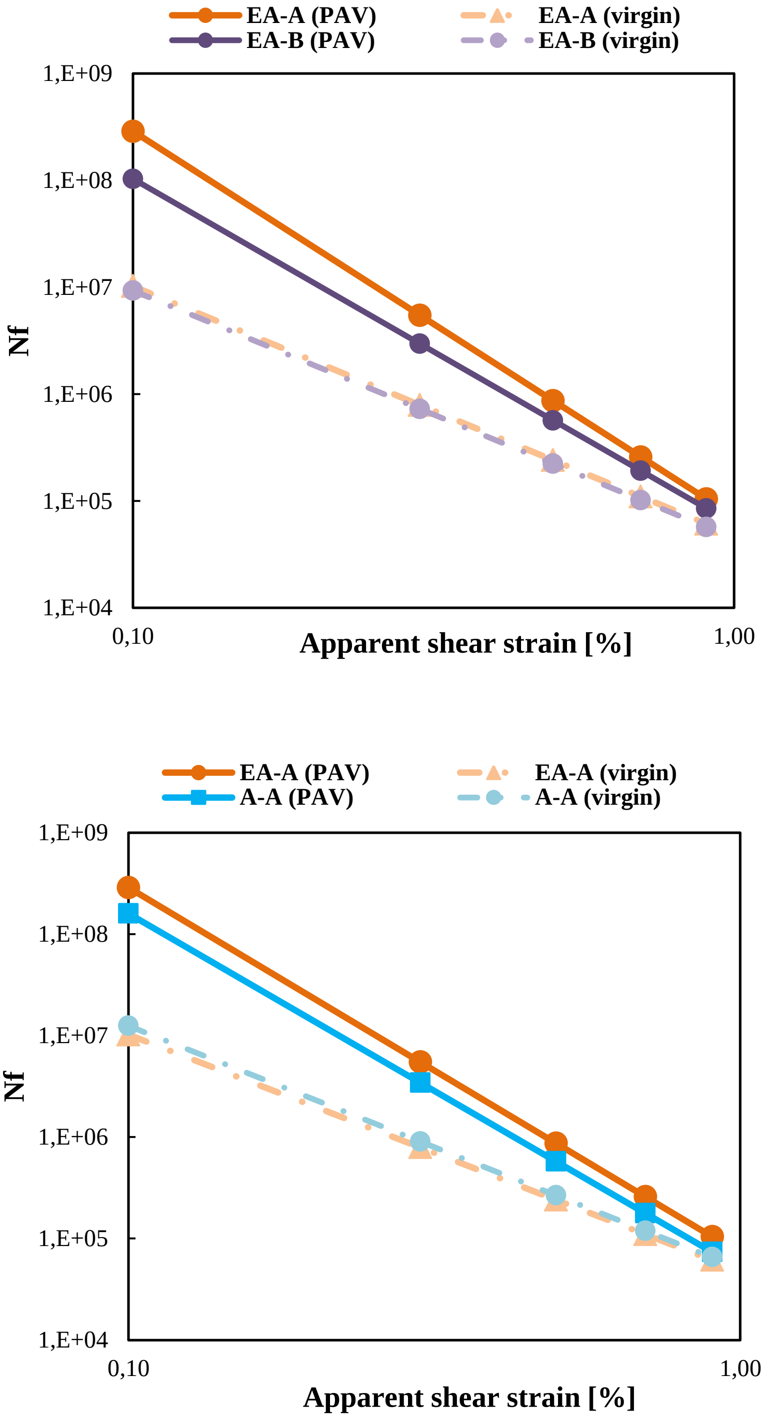


FIGURE 4 Comparison between experimental data and model fitting of LAS material integrity versus damage intensity curves of asphalt binder


EA-A (PAV)
EA-B (PAV)
EA-A (virgin)
EA-B (virgin)
1,E+10
1,E+09
1,E+08
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
Nf
0,10
1,00
Apparent shear strain [%]
EA-A (PAV)
A-A (PAV)
EA-A (virgin)
A-A (virgin)
1,E+10
1,E+09
1,E+08
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
Nf
0,10
1,00
Apparent shear strain [%]

(a)



(b)

FIGURE 5 Predicted fatigue life versus apparent shear strain at; (a) 10°C and (b) 20°C

(a)

(b)

FIGURE 6 View of in-plant automated distribution systems of epoxy modifier: (a) the storage tank of Part A in-line connected with the pugmill, and (b) Part B at ground level and from there pumped into the bitumen weighing distributor for the pugmill

FIGURE 7 View of (a) in-plant trial after applying tack coat (left) and during compaction (right); and in-field trial (b) during paving, and (c) after compaction