Exploring Master Curve Parameters to Distinguish between Mixture Variables

Mirkat Oshone[1], Jo Sias Daniel[2], Eshan Dave[3], Amy Epps Martin[4], Fawaz Kaseer [5], Reyhaneh Rahbar-Rastegar[6]

([1] University of New Hampshire, 33 Academic Way, NH, USA, mto1@wildcats.unh.edu)

([2] University of New Hampshire, 33 Academic Way, NH, USA, jo.daniel@unh.edu)

([3] University of New Hampshire, 33 Academic Way, NH, USA, eshan.dave@unh.edu)

([4] Texas A&M University, College Station, TX, USA, a-eppsmartin@tamu.edu)

([5] Texas A&M University, College Station, TX, 77843, USA, fawazkaseer@tamu.edu)

([6]Purdue University, West Lafayette, IN, USA, rrahbar@purdue.edu)

ABSTRACT

It is well known that mixture variables such as aging level, rejuvenator dosage, recycled binder ratio, and binder grade alter the rheological properties of asphalt concrete mixtures, subsequently affecting their performance in the field. Rheological evaluation can be employed through linear viscoelastic characterization in the form of dynamic modulus and phase angle master-curves. This study investigated the ability of dynamic modulus and phase angle master-curve parameters to capture the changes in mixture properties caused by aging, addition of rejuvenator, use of recycled material and change in binder grade by performing a comprehensive statistical analysis on 29 mixtures. Evaluated parameters included: the mixture Glover-Rowe parameter, inflection point frequency ($-\beta/\gamma$), difference between the glassy modulus and the inflection point modulus (γ), $-\beta/\gamma$ vs γ, and the lower and upper asymptotes of the sigmoidal master-curve. The effect of changes in mixture variables on master-curve parameters are qualitatively compared to expected mixture field performance as well. The study indicated the ability of all master-curve parameters to capture the effect of aging. In addition, the change in recycled material binder content is captured well by the G-R parameter, while $-\beta/\gamma$ and δ values were impacted by binder low temperature grade.

Keywords: dynamic modulus and phase angle master curve, master curve shape parameters, mixture variables, mixture performance

1. INTRODUCTION

It is well known that the common mixture variables such as aging level, rejuvenator use and dosage, content and type of recycled materials (Reclaimed Asphalt Pavement (RAP) or Recycled Asphalt Shingles (RAS)), and binder grade alter the rheological properties of asphalt concrete mixture which are important for design and modeling of asphalt pavements. The ability to understand the changes in rheological properties caused by changes in the mixture variables is beneficial to quantify the effect on mixture field performance. Rheological evaluation of asphalt concrete mixtures is commonly done by measuring the dynamic modulus ($|E^*|$) and phase angle (ϕ) to produce $|E^*|$ and ϕ master-curves for a range of temperature and frequency combinations. These two parameters can be determined at the mixture design or production stage directly by performing the complex modulus test (1) or indirectly from relaxation modulus and creep compliance tests through interconversion (2, 3). Moreover, different researchers have developed regression equations that can be used to determine dynamic modulus (4, 5, and 6) as well as phase angle (7, 8) values mainly from mixture design parameters. A study by Oshone et al. (9) proposed an approach for obtaining dynamic modulus master-curves from falling weight deflectometer (FWD) measurements taken throughout the pavement life. Due to the increasingly reliable and versatile ways to determine |E*| and ϕ master curves at different stages of the pavement life, researchers have tried to investigate the ability of master-curve parameters to track the changes in mixture properties due to different mixture variables (10, 11, 12). However, previous studies have not focused on a comprehensive statistical analysis to link the changes in mixture variables to master curves parameters.

In this study, a comprehensive statistical analysis was performed to investigate the ability of master-curve parameters to capture changes in mixture properties due to aging level, the addition of RAP/RAS, dosage of rejuvenator, and change in binder grade. Evaluated master-curve parameters are the mixture Glover-Rowe (G-R) parameter which relates |E*| and ϕ in Black space, and master-curve shape parameters (log of the inflection point frequency (-β/γ), log of the distance between the glassy modulus and the inflection point modulus (γ), -β/γ vs γ and lower and upper asymptotes of the sigmoidal form of the master curve). The effect of the changes in the parameters on performance due to variation in the mixture variables is described qualitatively. It is believed that the master curve parameters identified in this study can be used by mixture specifiers and producers during design, construction and service life of the pavement to determine the effect of the different mixture variables on performance.

2. MATERIALS AND METHODS

For this study 29 mixtures were used. The mixtures include eight mixtures from Texas, five mixtures from Nevada, three mixtures from Indiana and four mixtures from Wisconsin that are being evaluated as part of the NCHRP 9-58 project. The variables in these mixtures include aging levels (short-term oven aging (STOA) and long-term oven aging (LTOA)), rejuvenator dosage, recycled binder ratio (RBR, which defines the amount of RAP and RAS binder in the mixture as percent of total binder), binder grade (PGHT, high temperature performance grade and PGLT, low temperature performance grade) and PG spread (the difference between high and low temperature performance grade). Nine mixtures from New Hampshire (NH) are also included. These mixtures represent different percentages of RAP and RAS, binder grade and different aging levels (STOA and LTOA). The LTOA includes 5 days at 85ºC on compacted specimens, and 5 days at 95ºC, 24 hours at 135ºC and 12 days at 95ºC on loose mixture. Table 1 shows the mixture variables considered for the study along with the levels considered. All the mixtures were designed to optimum asphalt content using Superpave approach and test specimens were produced at a consistent air void level.

|E*| and ϕ master curves were produced using isotherms measured at three temperatures and six frequencies. A generalized sigmoidal equation with five parameters (indicated in Equation 1) was used to fit the |E*| master curves: w is loading frequency, δ is the lower asymptote, α is the difference between the values of upper and lower asymptote and λ, β and γ define the shape between the asymptotes and the location of the inflection point.

$$log|E^*| = \delta + \frac{\alpha}{\left(1+\lambda e^{[\beta+\gamma(logw)]}\right)^{1/\lambda}} \qquad \text{Eq. (1)}$$

The mixture G-R parameter in Black space and master-curve shape parameters investigated in this study are described below and are illustrated in Figures 1(a) and (b).

- Mixture G-R parameter (|E*| cosϕ^2/sinϕ) combines the |E*| and ϕ values to describe the stiffness and relaxation properties of an asphalt concrete mixture. For this study the parameter was determined at 15ºC and 5 rad/s to track the changes in mixture properties due to changes in mixture variables.

TABLE 1 Mixtures Information

Mixture Variables	Range of Mixture Variables				
	Texas	**Nevada**	**Indiana**	**Wisconsin**	**New Hampshire**
RBR (%)	0-50	0-30	0-42	27-36	20-30
Rejuvenator, %	0-12.5	0-2	0-3	1.2	-
PGHT, ºC	64, 70	64	59	52, 58	52, 58
PGLT, ºC	-22, -28	-28	-28	-28, -34	-28, -34
PG spread, ºC	86, 92	92	86	86	86
Aging level	5 days 85ºC[a]	5 days 85ºC[a]	5 days 85ºC[a]	5 days 85ºC[a]	5 days at 85 ºC[a] 5 days at 95 ºC[b] 24 hours at 135 ºC[b] 12 days at 95ºC[b]

[a] aging on compacted specimens [b] aging on loose mixture

- Log of the inflection point frequency (-β/γ) describes the elastic-viscous transition exhibited as a result of a shift from aggregate structure to binder dominating behavior. It marks the peak of the ϕ master curve or the inflection point in the |E*| master curve.
- Log of the distance between the glassy modulus and the inflection point modulus (γ) describes the width of the relaxation spectra and is computed from the difference between the glassy modulus and infection point modulus. As the |E*| master curve flattens. which typically happens with aging, the γ value increases.
- Lower (δ) and upper (δ+α) asymptotes represent the maximum and minimum points of the |E*| master-curves and are primarily related to aggregate properties.
- -β/γ vs γ shows the log of the inflection point frequency against the log of the distance between the glassy modulus and the inflection point modulus. This is similar to the plot of crossover frequency versus rheological index for binders. The points are expected to move to bottom right with aging and to the top left corner with the addition of rejuvenators as illustrated in Figure 1(b) [13]. In this study the effects from the two parameters are combined by calculating (-β/γ^2) and using the combined parameter in the regression analysis.

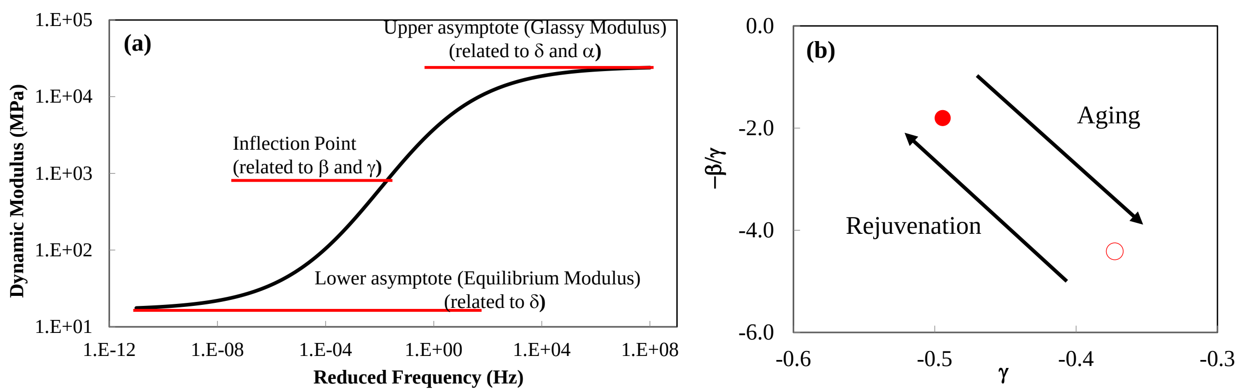

FIGURE 1 (a) |E*| Master Curve Shape Parameters (b) -β/γ vs γ Plot Schematically showing Hypothesis for Impacts of Aging and Rejuvenation

A stepwise regression analysis performs an iterative screening to determine the presence of a mathematical relationship between two variables such that a linear function of one can predict the other at a given confidence level. In this study a stepwise regression analysis was utilized to identify the significance of the different mixture variables on the master-curve parameters. The analysis made inferences about the larger population to recognize the ability of master-curve parameters to capture the changes in mixture properties caused by changes in mixture variables. This was accomplished by using the p-values from the analysis as an indicator for the existence of a relationship. For this study, the common practice of utilizing p-value < 0.05 is adopted and the null hypothesis is rejected for a p-value <0.05 indicating the mixture variables has contributed significantly to the changes observed in the master-curve parameter.

3. RESULTS AND DISCUSSION

The stepwise regression analysis performed on study mixtures was able to provide a platform to distinguish between master curve parameters that can track the changes in mixture properties due to aging level, RBR, rejuvenator dosage and binder grade. The p-values obtained from the analysis are presented in Table 2. A p-value < 0.05 was used as a threshold to identify the existence of a relationship between the mixture variables and the master-curve parameters. In other words, a p-value of <0.05 (indicated in **bold**) shows the ability of the master-curve parameter to capture the change in mixture property caused by the corresponding mixture variable.

TABLE 2 p-values from Stepwise Regression Analysis

Mixture Variables	**G-R Parameter**	**−β/γ vs γ**	**−β/γ**	**γ**	**δ**	**δ+α**
Aging	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
RBR	**0.05**	0.57	0.20	0.55	0.91	0.18
RA	0.90	0.90	0.89	0.32	0.70	0.30
PGHT	0.16	0.37	0.29	**0.05**	0.35	0.20
PGLT	**0.02**	0.49	**0.05**	0.11	**0.04**	0.25
ΔPG	0.67	0.80	0.59	0.71	0.35	0.95

Mixture G-R parameter - The regression analysis indicated the ability of the mixture G-R parameter to capture the changes in mixture properties caused by aging, RBR and PGLT of the binder (p-value for aging <0.001, RBR=0.05 and PGLT=0.02). The changes due to aging are shown in Black space diagram (Figures 2(a) and (b)), which similarly combines the effects of |E*| and ϕ in one plot. The plot shows that with aging the points shift towards the top left implying a change to a stiffer and less viscous material. For NH mixtures the shift increases as the aging level changes from 5 days at 85ºC to 5 days at 95ºC followed by 12 days at 95ºC and 24hr at 135ºC, Figure 2 (b). This increment in increasing stiffness and decreasing relaxation capacity is expected to increase the propensity of the mixture to cracking. In addition to the aging effect, the mixture G-R parameter appears to capture the effects of RBR and low temperature grade which also play a significant role in the cracking property of asphalt mixtures. The cumulative effect of these three parameters can be tracked and entered into a pavement performance prediction model to quantify the effect on field performance.

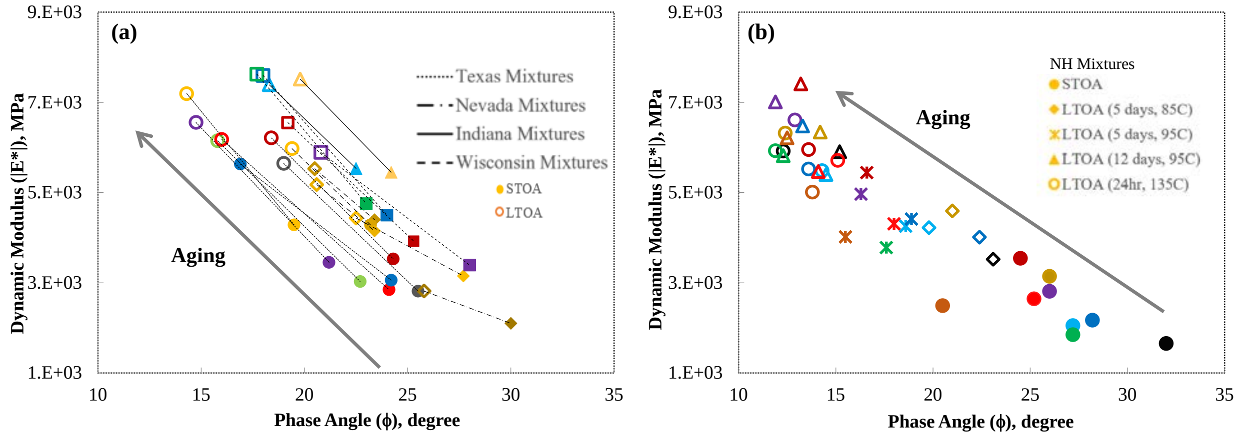

FIGURE 2 Shift in Black Space Points (15ºC and 5 rad/s) due to Aging (a) NCHRP Mixtures (b) New Hampshire Mixtures

$-\beta/\gamma$ vs γ parameter – The regression analysis indicated that the changes in the $-\beta/\gamma$ vs γ parameter are primarily impacted by aging (p-value <0.001). These changes in the $-\beta/\gamma$ vs γ points due to aging are shown in Figures 3 (a) and (b). The plots show that the $-\beta/\gamma$ vs γ points tend to shift towards the bottom right with aging. For NH mixtures the shift increases as the aging level changes from 5 days at 85ºC to 5 days at 95ºC followed by 12 days at 95ºC and 24hr at 135ºC which is a similar observation from the Black space plot in Figure 2 (b). This shift occurs due to the movement of the inflection point to the left in the |E*| master-curve as a result of the change in dominance of the binder at a lower loading frequency due to age induced decrease in viscosity. Moreover, with aging a larger width of the relaxation spectra is exhibited. A combination of the lower relaxation capacity and increased relaxation width results in a mixture that is more susceptible to thermal cracking. The researchers recommend the use of the $-\beta/\gamma$ vs γ plot when tracking changes in mixture properties only due to aging.

$-\beta/\gamma$ parameter - The $-\beta/\gamma$ parameter when considered separately appears to be influenced by both aging and PGLT of the binder. This indicates that a shift in inflection point frequency is mainly a result of a change in these two parameters and can be used to track the changes in material properties due changes in these two mixture variables.

γ parameter – The statistical analysis shows the ability of the γ parameter to capture the changes due to aging and PGHT of the binder. With aging, the dynamic modulus curve becomes flatter which increases the width of the relaxation spectra resulting in a greater propensity to thermal cracking.

Lower and upper asymptote- Both lower and upper asymptote appear to be affected by aging whereas only lower asymptote is impacted by PGLT.

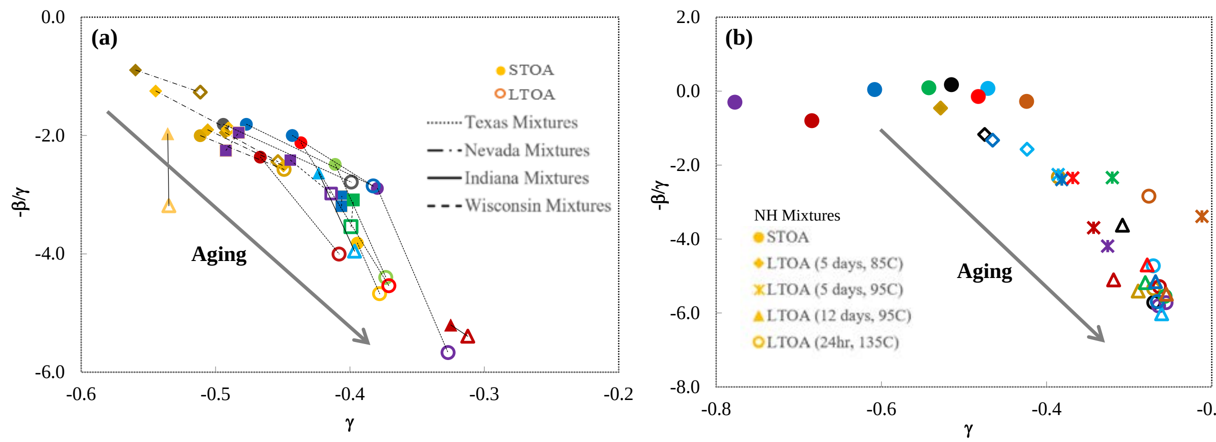

FIGURE 3 Shift in -β/γ vs γ Points due to Aging (a) NCHRP Mixtures (b) NH Mixtures

It should be noted that all master-curve parameters were able to capture the effect of aging whereas on the contrary the effects of rejuvenator were not captured by any of the parameters. The authors believe that the use of the low dosages and different types of rejuvenators for the mixtures obtained from Texas, Nevada, Indiana and Wisconsin could have impacted the mixture parameters differently resulting in the statistically insignificant effect of the rejuvenator on the rheological properties of the mixture. It is believed that the changes observed in the master-curve parameters can be attributed to changes in mixture field performance. Therefore, these changes can be entered into pavement performance prediction models to quantify the effect of aging level, addition of rejuvenator, recycled material binder content and binder grade on field performance of asphalt concrete mixtures.

4. SUMMARY AND CONCLUSION

In this study master-curve parameters such as the G-R parameter, log of the inflection point frequency (-β/γ), log of the distance between the glassy modulus and the inflection point modulus (γ), -β/γ vs γ and lower and upper asymptote of the sigmoidal form of master-curve were investigated to identify their ability to distinguish between mixture variables by performing a comprehensive statistical analysis. The evaluated mixture variables included aging level, rejuvenator dosage, RBR, and binder grade. A stepwise regression analysis conducted on the mixtures indicated that the mixture G-R parameter can capture the changes in mixture properties due to aging, RBR, and PGLT whereas the -β/γ vs γ parameter was able to capture the effect of aging only. A shift of Black space points to the top left has been observed with aging whereas the opposite trend was observed in the -β/γ vs γ plot which is associated more with cracking susceptibility in both cases.

Depending on the mixture specifier's or producer's interest in evaluating the effect of one or more of the mixture variables, the parameters identified in this study can be used to track the changes in rheological properties due to changes in specific mixture variables.

It is believed that the changes observed in the master-curve parameters can be attributed to changes in mixture field performance. Therefore, in future work these changes will be used to illustrate the changes in mixture field performance due to the presence of RAP/RAS, addition of rejuvenator, binder grade and aging level. This will be done by quantifying the changes in master-curve parameters and inputting the values into pavement performance prediction models.

5. REFERENCES

[1] American Association of State Highway and Transportation Officials, “Standard Method of Test for Determining Dynamic Modulus of Hot-Mixture Asphalt Concrete Mixtures,” AASHTO T342, 2012.

[2] Baumgaertel, M., and H. H. Winter. "Determination of discrete relaxation and retardation time spectra from dynamic mechanical data." Rheologica Acta 28, no. 6: 511-519, 1989.

[3] Park, S. W., and Y. R. Kim. "Interconversion between relaxation modulus and creep compliance for viscoelastic solids." Journal of materials in Civil Engineering 11, no. 1 76-82, 1999.

[4] Bari, Javed, and Matthew Witczak. "Development of a new revised version of the Witczak E* predictive model for hot mixture asphalt mixtures (with discussion)." Journal of the Association of Asphalt Paving Technologists 75, 2006.

[5] Christensen Jr, D. W., T. Pellinen, and R. F. Bonaquist. "Hirsch model for estimating the modulus of asphalt concrete." Journal of the Association of Asphalt Paving Technologists 72, 2003.

[6] Nemati, R. and Dave, E. “Nominal Property Based Predictive Models for Asphalt Mixture Complex Modulus (Dynamic Modulus and Phase Angle).” Construction and Building Materials, 2017 (In press).

[7] Rowe, G. "Phase angle determination and interrelationships within bituminous materials." In Proceedings of the 7th Int. RILEM Symposium on Advanced Testing and Characterization of Bituminous Materials, Rhodes, Greece, (Book 1, Edited by Loizos, Partl, Scapas & Al-Qadi), May, vol. 27, pp. 43-52, 2009.

[8] Oshone, M., Dave, E., Daniel, S. J., and Rowe, M. G., “Prediction of Phase Angles from Dynamic Modulus Data and Implications on Cracking Performance Evaluation,” Journal of Association of Asphalt Paving Technologists, 2017 (In Press).

[9] Oshone, M., Elshaer M, Dave E., Daniel J. Evolution of Asphalt Modulus from Falling Weight Deflectometer Tests and Challenges Associated with its Interpretation and Applications: A Case Study using LTPP Data. The 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields, 2017.

[10] Mensching, David J., Geoffrey M. Rowe, and Jo Sias Daniel. "A mixture-based Black Space parameter for low-temperature performance of hot mixture asphalt." Road Materials and Pavement Design 18, 404-425, 2017.

[11] Rowe, G., G. Baumgardner, and M. Sharrock. "Functional forms for master curve analysis of bituminous materials." In Proceedings of the 7th international RILEM symposium ATCBM09 on advanced testing and characterization of bituminous materials, vol. 1, pp. 81-91, 2016.

[12] Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin. “Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Rejuvenators.” Transportation Research Record: Journal of the Transportation Research Board, No. 2633, pp 58-68, 2017.

[13] Rowe, G. M. "Interrelationships in rheology for asphalt binder specifications." In Proceedings of the Fifty-Ninth Annual Conference of the Canadian Technical Asphalt Association (CTAA): Winnipeg, Manitoba, 2014.