2010

Material-Specific Effects of Hydrated Lime on the Properties and Performance Behavior of Asphalt Mixtures and Asphaltic Pavements

Francisco Thiago Sacramento Aragão
University of Nebraska-Lincoln, fthiago@huskers.unl.edu

Junghun Lee
University of Nebraska-Lincoln

Yong-Rak Kim
University of Nebraska-Lincoln, yong-rak.kim@unl.edu

Pravat Karki
University of Nebraska-Lincoln

Published in *Construction and Building Materials* 24 (2010), pp. 538–544;
doi: 10.1016/j.conbuildmat.2009.10.005

Submitted May 4, 2009; revised August 27, 2009; accepted October 15, 2009; published online November 12, 2009.

Material-Specific Effects of Hydrated Lime on the Properties and Performance Behavior of Asphalt Mixtures and Asphaltic Pavements

Francisco Thiago Sacramento Aragão,[1] Junghun Lee,[2] Yong-Rak Kim,[3] and Pravat Karki[4]

1. Department of Civil Engineering, W325.2 Nebraska Hall, University of Nebraska, Lincoln, NE 68588-0531, United States
2. Department of Civil Engineering, W332 Nebraska Hall, University of Nebraska, Lincoln, NE 68588-0531, United States
3. Department of Civil Engineering, W351 Nebraska Hall, University of Nebraska, Lincoln, NE 68588-0531, United States
4. Department of Civil Engineering, W333.3 Nebraska Hall, University of Nebraska, Lincoln, NE 68588-0531, United States

Corresponding author – Yong-Rak Kim, telephone 402-472-1727, email ykim3@unl.edu

Abstract

This study evaluates hydrated lime-treated hot-mix asphalt (HMA) mixtures through various laboratory tests, including the dynamic modulus test and performance tests to characterize permanent deformation and fatigue damage resistance both in displacement-controlled and force-controlled modes. Two different asphalt mixtures—the asphalt concrete mixture and the fine aggregate asphalt matrix mixture—which differ only in the amount of additional hydrated lime (0.5–3.0%), are tested. Test results demonstrate material-specific damage characteristics of hydrated lime and the existence of a more appropriate amount of hydrated lime to be added to the HMA mixtures than the current typical application rate such as the addition of 1.0% lime to dry or premoistened aggregates. In addition, the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG) is used for predicting pavement performance related to hydrated lime content. The MEPDG analysis results show that damage prediction models implemented in the current MEPDG are limited to accurately predicting material-specific damage characteristics. Mechanistic models that consider material-specific crack phenomenon and fracture behavior should be pursued.

Keywords: hot-mix asphalt, hydrated lime, pavement performance, Mechanistic-Empirical Pavement Design Guide

1. Introduction

Hydrated lime has shown multifunctional effects in hot-mix asphalt (HMA) mixtures. Numerous studies have demonstrated that hydrated lime in asphalt mixtures can reduce pavement rut-depth because of its distinct stiffening effects [1–3], moisture-associated damage by improving the aggregate-asphalt bonding [3–5], and long-term oxidative aging potential [1,3,6]. Several experimental studies have also shown that hydrated lime can reduce asphalt cracking to some extent despite its stiffening effects because the initial microcracks can be intercepted and deflected by tiny, active lime particles. Kim et al. [7,8] performed experimental studies and mechanical analyses that clearly showed fatigue crack-resistant characteristics of hydrated lime-treated asphalt mixtures using cylindrical sand asphalt samples and a dynamic mechanical testing protocol. Because of the latest observations that hydrated lime is an efficient material for improving fatigue cracking resistance as well as rutting, which is not a typically observed phenomenon from other materials, the effects of hydrated lime as a crack resister have remained unsolved questions and have not been fully understood in the asphalt pavement community. Moreover, not many studies have been conducted to investigate the crack-resistant characteristics of hydrated lime–treated mixtures with different application rates. Since stiffer mixtures are generally more susceptible to cracking, the crack-resistant characteristics of hydrated lime might be degraded from certain critical amounts of lime added, whereas the rut-resistant potential of mixtures can still be enhanced.

Many states in the US have used hydrated lime primarily to mitigate moisture-related damage by adding approximately 1.0% hydrated lime in the design of HMA mixtures. The addition of 1.0% lime to dry or premoistened aggregates may not be the best scenario to maximize pavement material properties and performance when various pavement distresses are considered together. Furthermore, the effect of hydrated lime on the stiffness of the mixtures, generally represented by dynamic moduli today, becomes a very important issue given that dynamic modulus is the key input property that characterizes the mixture stiffness and pavement performance in the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG) [1,9,10]. A more appropriate amount of hydrated lime in HMA mixtures needs to be investigated scientifically, if it even exists.

In addition to the aforementioned information related to the effects of hydrated lime as a fatigue damage resister, research efforts have attempted to reduce the time required for the characterization of fatigue behavior of asphalt concrete mixtures. Fatigue testing of asphalt concrete samples is typically time-consuming and costly. An example to reduce the effort required for the characterization of asphalt concrete fatigue behavior is the work by Wen and Kim [11], Kim et al. [12], and Kim and Wen [13]; the authors proposed a simple testing method based on the fracture energy at 20°C of 100-mm diameter indirect tensile (IDT) specimens. They presented a good agreement of the IDT fracture energy measurements to the field-cracking indices. Another effort was recently made by Kim et al. [14–16], where small cylindrical samples of fine aggregate asphalt matrix mixtures (composed of binder, fine aggregates, and fillers) were tested in a dynamic mechanical analysis (DMA) testing program to characterize the linear viscoelastic stiffness and the fatigue performance of the matrix mixtures. The DMA test was capable of significantly reducing experimental costs and the time necessary for the characterization of the fatigue behavior of asphalt concrete mixtures. Subsequent studies [17–19] following the work by Kim et al. [14–16] showed that the fatigue behavior of asphalt concrete mixtures is closely related to the fracture characteristics of the asphalt matrix mixtures tested in the DMA system.

The new MEPDG has been recently proposed, and many state transportation agencies and researchers have already begun its adaptation and local calibration. To traditional pavement design approaches, the MEPDG is a significant improvement in that the guide models pavement materials and structural behavior based on the use of fundamental material characteristics and mechanistic theories to a certain extent, so that more realistic predictions of pavement responses and performance can be made. However, in spite of the significant advancements, the MEPDG remains challenging when accurately predicting damage-related mechanical responses in asphaltic pavements due to some simplifications, such as the use of axisymmetric layered elastic theory for pavement structural analyses, simplified constitutive relations and fracture-damage models for paving materials, and the use of circular tire loading configurations.

2. Objective and scope of this study

The primary objective of this study is to seek better insights into material-specific effects of hydrated lime as a crack resister. As mentioned earlier, the effects of hydrated lime to reduce pavement rut-depth and moisture-associated damage have been studied by many researchers, but the effects of hydrated lime as a crack resister have not been fully understood in the asphalt pavement community. Moreover, few attempts have been made to investigate the crack-resistant characteristics of hydrated lime-treated mixtures with different application rates.

To this end, this study investigated fundamental material properties and performance characteristics of hydrated lime-treated materials using two different types of asphalt mixture, i.e., the asphalt concrete mixture for general evaluations and the fine aggregate asphalt matrix mixture for quick evaluations, with different amounts of hydrated lime through various experimental approaches and MEPDG performance simulations.

Laboratory tests included evaluation of mixture stiffness in the form of the linear viscoelastic dynamic modulus and characterization of damage-related performance: permanent deformation and fatigue damage both in displacement-controlled and force-controlled modes. Laboratory test results were then applied to the MEPDG as input parameters to predict pavement performance related to the hydrated lime content.

3. Materials and specimen fabrication

One Superpave PG 64–28 binder, six types of aggregates, and hydrated lime were used in this study. Five mixtures (F05, F10, F15, F20, and F30) were prepared with the same blend of aggregates to keep aggregate angularities and mineralogical characteristics constant. The only variable in the mixtures was the amount of hydrated lime as shown in table 1.

Table 1. The five mixtures prepared for this study

Mixture component	F05	F10	F15	F20	F30
Asphalt binder	The same binder PG 64–28 to all mixtures				
Coarse aggregates Fine aggregates	The same blend and amount of aggregates to all mixtures				
Filler (less than 75 μm)	3.5% (by total weight of aggregates) to all mixtures				
Additive: HL[a] (%)	0.5	1.0	1.5	2.0	3.0

a. HL (%): Hydrated lime (% addition by total weight of aggregates)

With the mixture preparations completed, asphalt concrete samples were compacted using the Superpave gyratory compactor. Each compacted sample was cut and cored to produce (1) IDT specimens (100-mm in diameter and 38-mm tall) to perform fatigue tests in force-controlled mode, (2) IDT specimens (100-mm in diameter and 38-mm tall) for permanent deformation tests, (3) uniaxial tensile testing specimens (75-mm in diameter and 115-mm tall) to perform fatigue tests in displacement-controlled mode, and (4) uniaxial tensile testing specimens (100-mm in diameter and 150-mm tall) to perform dynamic modulus tests.

For the asphalt matrix specimens, the binder was mixed with fine aggregates (smaller than 0.60 mm) and hydrated lime. The asphalt binder content of each matrix mixture was calculated to meet an average film thickness of 12 μm. Each specimen was produced in a specially fabricated mold by putting the loose asphalt matrix mixture into the mold and then compacting the loose mixture. The 13 g of loose mixture was determined by matching volumetric characteristics of the asphalt matrix specimen with the volumetric characteristics of asphalt concrete mixtures to produce a cylindrical specimen (50-mm long and 12 mm in diameter). A more detailed description of the asphalt matrix specimen fabrication can be found in previous studies [14–16].

4. Laboratory tests

Table 2 summarizes the laboratory tests performed in this study. Mixture stiffness was measured in the form of the linear viscoelastic dynamic modulus for both the asphalt concrete mixture (in uniaxial tensile mode) and the asphalt matrix mixture (in torsional shear mode). Fatigue damage of the mixtures was characterized in both force-controlled and displacement-controlled modes. For the asphalt concrete mixture, the IDT and the uniaxial tensile fatigue tests were conducted for the force-controlled and displacement-controlled mode, respectively. For the asphalt matrix mixture, the torsional mode of DMA testing was performed for both force-controlled (or stress-controlled) and displacement-controlled (or strain-controlled) tests. The purpose of attempting two different loading modes (i.e., force-controlled and displacement-controlled) for the fatigue tests in this study was to investigate the impact of hydrated lime with different addition rates on fatigue resistance in general field conditions where combined effects of loading modes most likely exist. One of the well-known arguments in the asphalt pavement community is that the force-controlled loading mode is more appropriate to represent the fatigue behavior of thick asphalt layers (thicker than 15 cm), whereas the displacement-controlled testing is in better agreement with thin layers (less than 5 cm) [20,21]. By performing the fatigue tests in both loading modes, the material-specific effects of hydrated lime can be better estimated. Mixture resistance to permanent deformation was also investigated by performing the IDT test of asphalt concrete mixtures. Table 2 also lists the number of replicates in each test, the parameters monitored throughout each test, and their failure criteria adopted to define the mixture failure of each performance test.

Table 2. Testing modes and failure criterion for all the tests

Laboratory test	Mixture type	Testing mode (No. of replicates)	Parameter monitored	Failure criterion
Dynamic modulus	Asphalt concrete	Uniaxial (2)	LVE[a] |E*|	—
	Asphalt matrix	Torsional (2)	LVE |G*|	—
Fatigue cracking	Asphalt concrete	IDT (in F-C[b]) (2–4)	Horizontal deformation	
		Uniaxial (in D-C[c]) (2–3)	Stiffness	
				Transition point
	Asphalt matrix	Torsional (in F-C) (3)	Compliance	
		Torsional (in D-C) (4)	Stiffness	
Permanent deformation	Asphalt concrete	IDT (2)	Vertical deformation	

a. LVE: Linear viscoelastic

b. F-C: Force-controlled

c. D-C: Displacement-controlled

4.1. Dynamic modulus tests of asphalt concrete mixtures

Dynamic modulus tests were performed on cylindrical asphalt concrete specimens in the uniaxial testing mode. The loading levels were carefully adjusted until the strain levels were within the range of 0.00005–0.000075. Three linear variable differential transformers (LVDTs) were mounted onto the surface of the specimen at 120° radial intervals with a 100-mm gauge length. Averaged vertical deformations were used to calculate the dynamic modulus, defined simply as the ratio of the sinusoidal stress amplitude to the sinusoidal strain amplitude. As suggested in the AASHTO TP 62-03 [22], five temperatures (–10°C, 4.4°C, 21.1°C, 37.8°C, and 54.4°C) and six loading frequencies (25, 10, 5, 1.0, 0.5, and 0.1 Hz) were used, and the frequency-temperature superposition concept was applied to develop each master curve representing the dynamic modulus of each mixture.

4.2. Dynamic modulus tests of asphalt matrix mixtures

For the asphalt matrix specimens, dynamic strain sweep and dynamic frequency sweep tests were performed. The strain sweep tests were used to identify a range of strain levels that guaranteed linearity for the frequency sweep tests, which eventually produce the linear viscoelastic dynamic shear modulus of each matrix mixture. From a series of strain sweep tests at different loading frequencies and temperatures, a strain of 0.0065% was finally determined to be used for the frequency sweep tests since the 0.0065% strain was low enough not to cause any nonlinearity for the frequency sweep tests. The frequency sweep tests were then conducted within a range of frequencies (0.01–25 Hz) and at three different temperatures (5°C, 20°C, and 40°C) to generate a master curve of each matrix mixture.

4.3. Performance tests of asphalt concrete mixtures

Fatigue tests of asphalt concrete mixtures were conducted at 20°C and at 10 Hz. As mentioned, the force-controlled loading mode was used to characterize the fatigue behavior of the IDT specimens, while the displacement-controlled mode was used for the uniaxial tensile fatigue tests. The use of two different geometries for the fatigue tests in this study was based on a study by Kim and Wen [13]. They demonstrated that IDT testing is advantageous because it is relatively simple and expedient to perform but should not be used to characterize fatigue in the displacement-controlled loading mode.

For the tests in the IDT force-controlled mode, a 1.5 kN compressive sinusoidal load was applied to the specimens, and horizontal deformations were monitored and used to determine the failure of the specimen. Failure was considered to occur when the constant rate of increase of the horizontal deformations was replaced by a faster rate of increase of the deformations. As a representative example, figure 1 presents a specimen under progressive fatigue damage leading to failure defined at a point (referred to as a transition point herein) where many microcracks in the specimen were combined into several macrocracks, which resulted in the specimen splitting into two pieces.

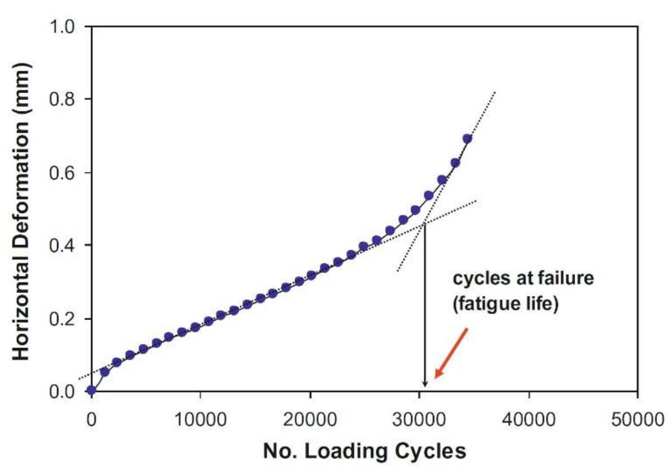

Figure 1. An example plot of the force-controlled IDT fatigue test at 20°C.

For the displacement-controlled tests, sinusoidal axial tensile strains with amplitude of 0.0017 were applied to the cylindrical specimens. The failure criterion chosen was based on several studies including those by Kim et al. [8] and Lee et al. [23]. According to these studies, the transition point between two inflection points in the stiffness and the loading cycle plot is the most appropriate measure when fatigue failure occurs as it represents the shift from microcracking to macrocracking. The rate of stiffness reduction drastically increased at that transition point when the macrocracks started to form. The authors also showed good agreement between the number of loading cycles at the transition point and at the peak phase angle. This failure criterion has been considered a more logical and better estimate of fatigue failure of asphalt mixtures than arbitrarily using the 50% reduction in stiffness as a failure criterion. As an example plot, figure 2 presents the failure criterion determined by the transition point.

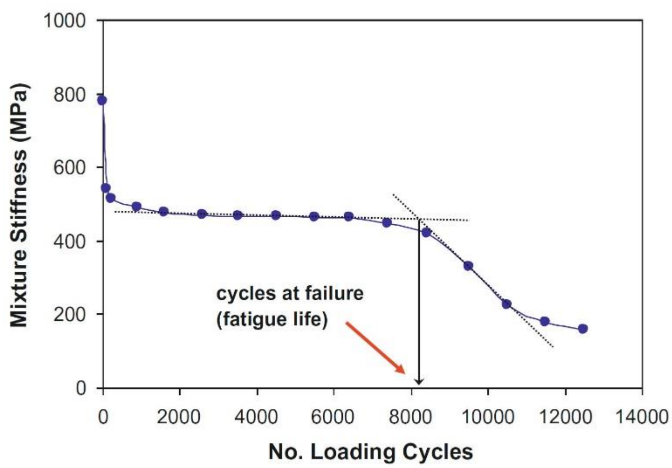

Figure 2. An example plot of the displacement-controlled fatigue test at 20°C.

In addition to the fatigue tests, the rutting potential of asphalt concrete mixtures with different amounts of hydrated lime was characterized by conducting the IDT tests at a high temperature condition of 60°C. A constant load of 0.27 kN was applied to the specimens, and the vertical deformation (in compression) was monitored and used to determine the failure of the specimen. The failure point due to plastic flow was determined at the transition stage from secondary creep to tertiary creep as demonstrated in the actuator displacement-time curve shown in figure 3.

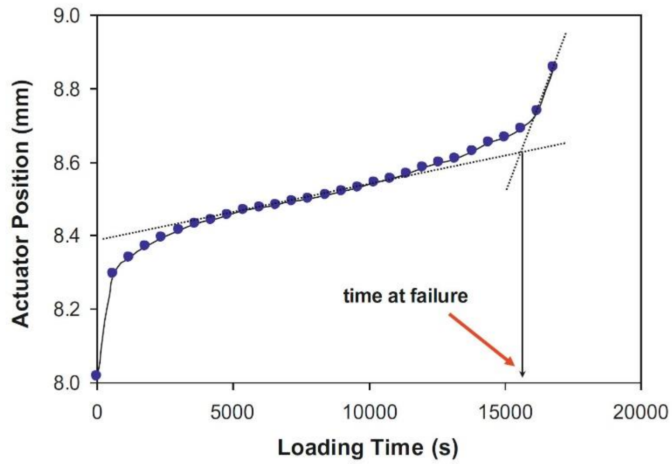

Figure 3. An example plot of the IDT permanent deformation test at 60°C.

4.4. Performance tests of asphalt matrix mixtures

Similar to the fatigue tests of asphalt concrete mixtures, the asphalt matrix specimens were tested in the torsional loading mode in the DMA equipment at 25°C and at 10 Hz. For the force-controlled (or stress-controlled) tests, the shear stress of 35 kPa was applied to each matrix specimen, and mixture compliance, which is the ratio of measured strain amplitude to the applied stress amplitude, was monitored as the number of loading cycles continued. For the displacement-controlled (or strain-controlled) tests, a level of 0.30% shear strain was used, and mixture stiffness, which is defined as the ratio of stress output to the applied strain input, was calculated during the fatigue test. The failure criteria adopted were similar, as described for the fatigue tests of asphalt concrete mixtures (fig. 1 and 2). The transition point was captured as a fatigue failure point.

5. Test results and discussion

5.1. Dynamic modulus test results

Figure 4 shows the dynamic modulus master curves of all five asphalt concrete mixtures at the reference temperature of 20°C. As shown, the dynamic moduli of asphalt concrete mixtures were not significantly sensitive to the amount of hydrated lime at the intermediate to high loading frequencies, while a more sensitive effect of hydrated lime in stiffening mixtures was observed at low loading frequencies. The dynamic moduli increased as the amount of hydrated lime in the mixture increased at low frequencies (i.e., high temperature conditions).

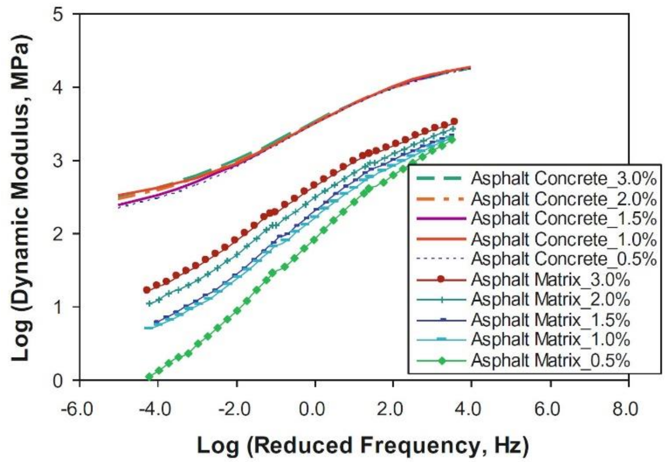

Figure 4. Dynamic modulus curves of all asphalt mixtures at 20°C.

Figure 4 also presents the dynamic shear modulus curves of asphalt matrix mixtures at the reference temperature (20°C). As shown, the stiffening effect of hydrated lime is much more obvious from the matrix testing than the asphalt concrete testing. The position of the modulus curves further demonstrates that hydrated lime stiffened the mixtures. A general trend seen in the figure is that the asphalt matrix mixture containing the more hydrated lime exhibited higher stiffness, and the sensitivity of the effect of hydrated lime on mixture stiffening was greater at lower loading frequencies, which is in good agreement with the test results from asphalt concrete mixtures.

As mentioned in previous sections, the loading frequency used in this study to characterize the fatigue behavior of each mixture was 10 Hz. Therefore, the intention was to observe the dynamic modulus of each mixture at the loading frequency of 10 Hz, since the dynamic modulus at 10 Hz represented the material stiffness of each mixture subjected to fatigue tests at the same loading frequency. The dynamic moduli of all five mixtures at 10 Hz are compared in figure 5. For a more distinct comparison, normalized dynamic moduli to the value from the 0.5% hydrated lime mixture were plotted in the figure. As shown, the difference in stiffness among asphalt concrete mixtures was not significant, whereas asphalt matrix samples exhibited the stiffening effect of hydrated lime in a much more sensitive manner.

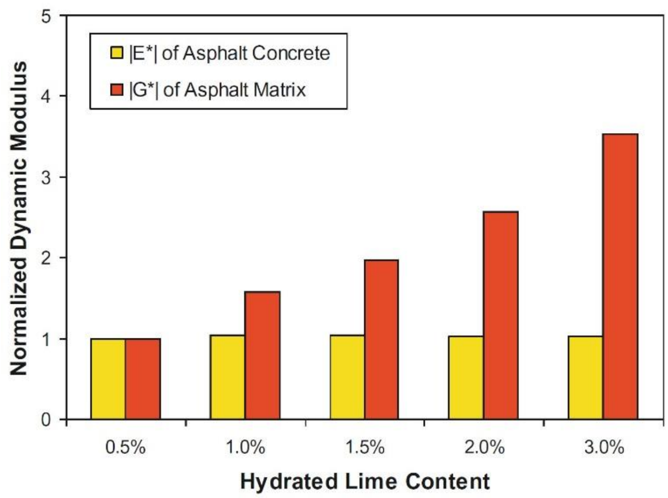

Figure 5. Normalized dynamic moduli of mixtures at 10 Hz.

5.2. Performance test results

Figure 6 shows the number of cycles to failure in the force (stress)-controlled mode. There was an increasing trend in the resistance to fatigue damage as more hydrated lime was added to the mixtures. This was an expected phenomenon since the addition of hydrated lime resulted in stiffer mixtures as demonstrated in figures 4 and 5. Stiffer mixtures usually lasted longer under the force-controlled fatigue testing because stiffer materials are better resistant to cracking under the force-controlled condition, which is typically the opposite in displacement-controlled testing. The only mixture violating the increasing trend of fatigue damage resistance was the mixture with 1.5% of hydrated lime. The 1.5% hydrated lime mixture performed better than the mixture with 2.0% hydrated lime, and this was true for both the asphalt concrete and the asphalt matrix. To explain the test results at this moment better, a more conclusive finding should be made with more test data and additional mechanistic data analyses based on the nonlinear viscoelastic theory and the continuum damage mechanics approach [12,24–26], which are currently under investigation by the authors.

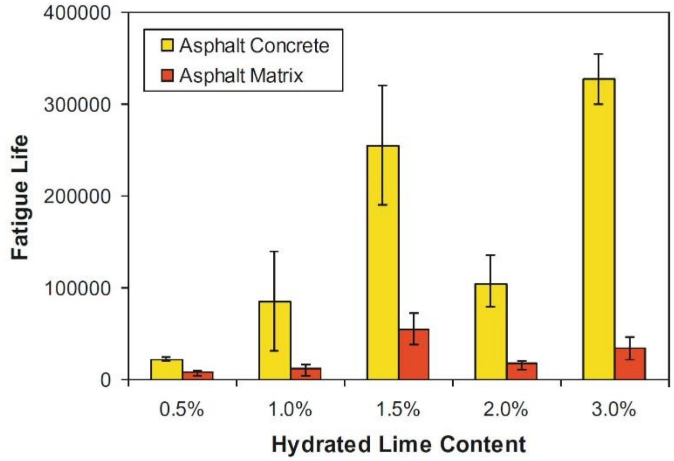

Figure 6. Force-controlled fatigue test results.

Figure 7 shows the number of cycles to failure in the displacement-controlled fatigue tests. The tests resulted in a different optimality from the force-controlled tests. Results show that the best performance was at the 1.5% hydrated lime, and the addition of extra quantities of hydrated lime resulted in mixtures less resistant to fatigue damage. Several studies including a study by Kim et al. [7] demonstrated that hydrated lime provided better resistance to microcracking and thus, an increased fatigue life under the displacement-controlled testing mode, even if mixtures stiffened due to the addition of hydrated lime. Since stiffer mixtures are generally more susceptible to cracking such as fatigue damage under the displacement-controlled condition, the better performance observed in the case of hydrated lime-mixed asphalt concrete mixtures was interpreted to be an indicator that explains the positive effects of hydrated lime on fatigue damage resistance by its toughening mechanisms. However, the toughening can be impeded by adding a critical amount of hydrated lime, which produces mixtures that are prone to cracking due to material brittleness as shown in figure 7. The contribution of hydrated lime to fatigue damage resistance depended on the amount of hydrated lime.

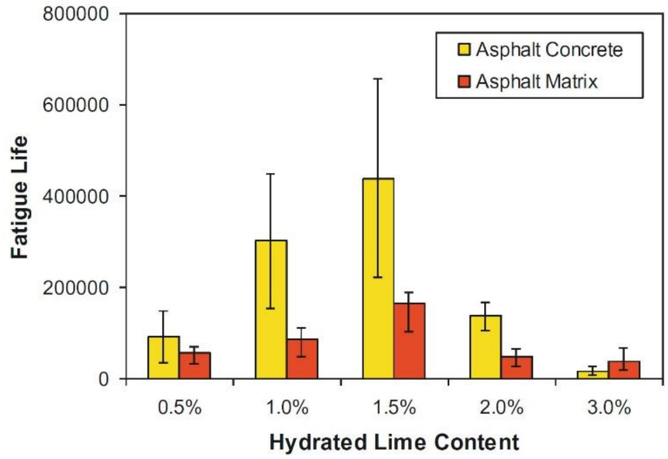

Figure 7. Displacement-controlled fatigue test results.

Figure 8 shows the results obtained from the permanent deformation tests of asphalt concrete mixtures at 60°C. A clearly increasing trend of resistance to rutting occurred as more hydrated lime was added to the mixtures, which is in good agreement with the dynamic modulus test results at high temperature conditions (i.e., low loading frequencies) as shown in figure 4. From figure 8, it also appears that the addition of more than 2.0% of hydrated lime did not improve the resistance of the mixtures to permanent deformations, as the time to failure for the 3.0% case was not statistically different from the time to failure of the 2.0% case.

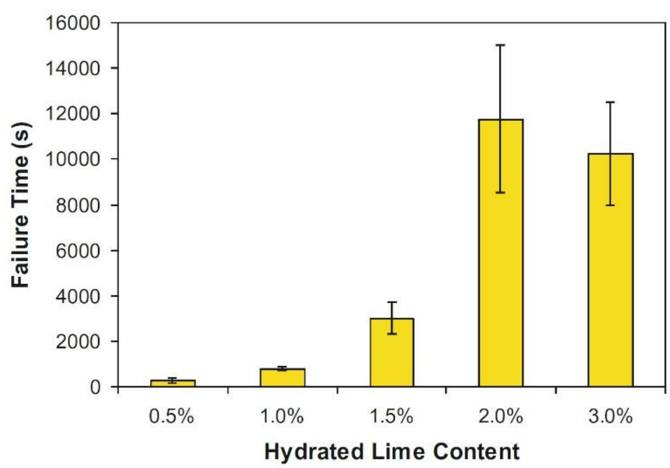

Figure 8. Permanent deformation test results from asphalt concrete mixtures.

As shown in figures 4–8, hydrated lime generally improved the properties and performance of the mixtures. Although there were clear trends in each test, it should be noted that because of the nature of the tests, both fatigue tests and permanent deformation tests exhibited relatively high testing variability, which is seen from the error bars in the figures. Additional tests are recommended to support test results herein and to explain the related mechanisms better. One more thing commonly observed from this study is that the test results conducted with asphalt matrices in the DMA followed very closely those obtained from the asphalt concrete mixture specimens. Moreover, the DMA testing with asphalt matrix mixtures could significantly save testing time and efforts by improving its testing efficiency (with less testing time, less fabrication efforts, and more economical testing systems). Due to fast, simple, and efficient characteristics, the use of the DMA tests to characterize the properties and performance of asphalt mixtures can be encouraged.

6. Pavement performance predictions through MEPDG

In an attempt to evaluate the effects of material-specific characteristics of hydrated lime added in asphalt mixtures on mechanical performance of asphaltic pavements, this study used the MEPDG to simulate the performance of asphaltic pavements with five different HMA mixtures (i.e., F05–F30). Simulation results were then qualitatively compared with laboratory performance testing results.

The dynamic moduli and the volumetric parameters of the five HMA mixtures being investigated herein were used in the simulations for three different asphaltic pavement structures (Pavements A, B, and C) as illustrated in table 3. MEPDG inputs related to traffic and climate were simplified to better compare with laboratory performance test results. Only one type of vehicle, "Class 9," classified in the MEPDG was applied to all three cases, and two different temperatures, 21.1°C and 48.9°C, were selected to simulate the fatigue and permanent deformation laboratory tests, respectively. Displacement-controlled loading conditions were imposed for the simulations of fatigue tests for thin (50.8 mm) surface layers and force-controlled loading conditions were used for the characterization of the fatigue performance of thick (203.2 mm) surface layers [21]. Other input parameters, such as thicknesses and material properties of different layers, were kept constant to purely investigate the effect of hydrated lime-specific pavement performance.

Table 3. Pavement structures and MEPDG inputs

Layer	Pavement A	Pavement B	Pavement C
Surface			
Type	HMA	HMA	HMA
Thickness (mm)	50.8	203.2	203.2
Base			
Type	A–1–b	A–1–b	A–1–b
Thickness (mm)	38.1	38.1	38.1
Subbase			
Type	A–5	A–5	A–5
Thickness (mm)	30.48	30.48	30.48
Subgrade			
Type	A–5	A–5	A–5
Temperature (°C)	21.1	21.1	48.9

Figure 9 shows MEPDG simulation results from Pavement C, where the permanent deformation (rutting) results at the constant temperature of 48.9°C are compared. A clear trend of resistance to rutting was observed as more hydrated lime was added to the mixtures. Figure 9 is in good agreement with the laboratory permanent deformation testing (in fig. 8) and the dynamic modulus testing (in fig. 4) results.

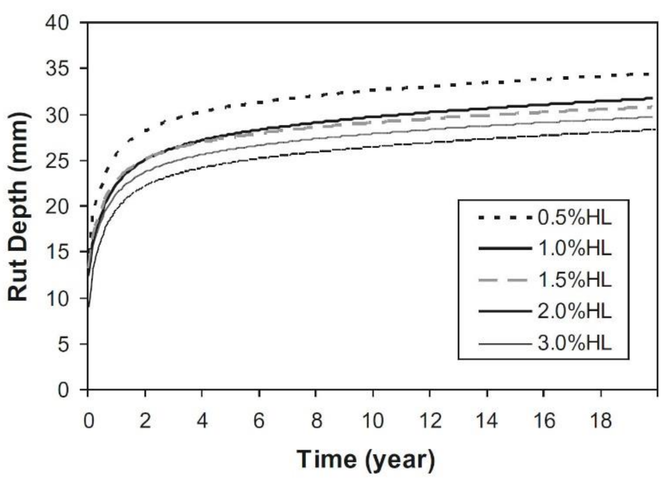

Figure 9. MEPDG predictions of pavement rut depth.

Figure 10 presents simulation results from Pavements A and B where the percent of bottom-up cracking (i.e., fatigue cracking) predicted over a time span of 20 years is illustrated for the thin pavement (Pavement A) and the thick pavement (Pavement B). A comparison between the results shown in figures 7 and 10 demonstrates that for thin pavements, the trends observed for potential fatigue cracking from the MEPDG analysis and for the displacement-controlled laboratory fatigue test are similar. However, this similarity is not observed for the thick pavement analyses. As presented in figures 6 and 10, for the laboratory testing results, the mixture with 3% lime was the one that experienced the least fatigue damage, whereas the MEPDG analysis ranked that mixture as the weakest, even if the fatigue cracking sensitivity among mixtures from the thick pavement MEPDG analyses was not clearly found. Based on observations herein, it can be inferred that the MEPDG are somewhat limited when accurately predicting material-specific fracture characteristics due to the empirical nature of the MEPDG fracture-damage models. Mechanistic models that consider material-specific crack phenomenon and appropriate fracture properties obtained from proper laboratory tests are therefore necessary.

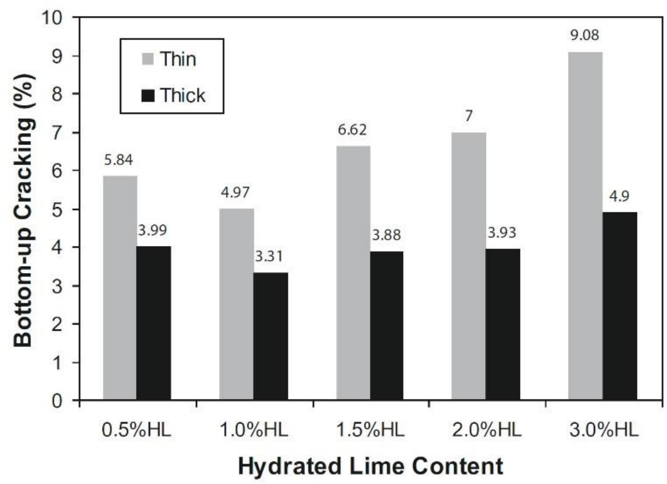

Figure 10. MEPDG predictions of pavement bottom-up cracking.

7. Summary and conclusions

Fundamental material properties and performance characteristics of asphalt mixtures treated with different amounts of hydrated lime were investigated through various experimental approaches and MEPDG performance simulations. Based on this study, the following summary and conclusions can be made:

- Hydrated lime generally improved the stiffness of HMA mixtures. The effect of hydrated lime content on mixture stiffness was not highly sensitive at the intermediate to high loading frequencies, whereas a clear effect of hydrated lime in stiffening mixtures was observed at lower loading frequencies. The greater stiffening effects of hydrated lime at low loading frequencies explain the performance improvement of rut resistance in the asphalt mixtures at high temperature conditions.
- For the fatigue tests in the force-controlled mode, there was a generally increasing trend in resistance to cyclic loading as more hydrated lime was used with an exception at the 1.5% hydrated lime addition in this particular study. The increasing

trend was expected because, in general, the fatigue lives of stiffer mixtures in force-controlled mode are longer.

- Fatigue test results in the displacement-controlled mode showed that the better resistance to microcracking obtained with the use of hydrated lime depended on the amount added to the mixtures. There was a clear indication of the positive effects of hydrated lime on fatigue damage resistance by its fracture toughening mechanisms related to physicochemical interactions with binder and mineral aggregates [6,7]; however, the toughening was impeded by adding a critical amount of hydrated lime, which produces mixtures that are prone to cracking due to material brittleness.
- The resistance of the mixtures to permanent deformations was exponentially improved as more hydrated lime was added. However, it was also observed that there is a critical amount (2.0% in this particular study) where no additional improvement in performance was obtained.
- The test results conducted with asphalt matrices in the DMA very closely followed those observed from the asphalt concrete mixtures. Because of the reduced testing time and improved efficiency, the use of the tests in the DMA as a simple, fast, and economical approach to characterize the fundamental properties and performance of asphalt mixtures can be encouraged.
- Based on the overall test results, it is concluded that there is a more appropriate application of hydrated lime into asphalt mixtures to improve overall pavement performance considering the various modes of pavement distress. An optimized scenario can be obtained by taking into account fundamental material properties and various performance characteristics altogether.
- The MEPDG analysis results showed that damage prediction models implemented in the current MEPDG are somewhat limited when accurately predicting material-specific fracture characteristics. Mechanistic models that consider crack phenomenon and fracture behavior are recommended.
- This study only presented laboratory test results and related numerical simulations. Field performance test results and mechanistic analyses of test data that can support findings from this study should be sought. This validation process is in progress by the authors.

Acknowledgment – The authors acknowledge the Nebraska Department of Roads for the financial support.

References

[1] Bari J, Witczak MW. Evaluation of the effect of lime modification on the dynamic modulus stiffness of hot-mix asphalt. Transport Res Rec 2005;1929:10–19.

[2] Mohammad LN, Abadie C, Gokmen R, Puppala AJ. Mechanistic evaluation of hydrated lime in hot-mix asphalt mixtures. Transport Res Rec 2000;1723:26–36.

[3] Little DN, Epps JA, and Sebaaly PE. The benefits of hydrated lime in hot mix asphalt. National Lime Association; 2006.

[4] McCann M, Sebaaly PE. Evaluation of moisture sensitivity and performance of lime in hot-mix asphalt resilient modulus, tensile strength, and simple shear tests. Transport Res Rec 2003;1832:9–16.

[5] Kim Y, Lutif JS, Bhasin A, Little DN. Evaluation of moisture damage mechanism and effects of hydrated lime in asphalt mixtures through measurements of mixture component properties and performance testing. J Mater Civ Eng 2008;20(10):659–67.

[6] Little DN, Petersen JC. Unique effect of hydrated lime filler on the performance-related properties of asphalt cement: physical and chemical interactions revisited. J Mater Civ Eng 2005;17(2):207–18.

[7] Kim Y, Little DN, Song I. Effect of mineral fillers on fatigue resistance and fundamental material characteristics: mechanistic evaluation. Transport Res Rec 2003;1832:1–8.

[8] Kim Y, Lee HJ, Little DN, Kim YR. A simple testing method to evaluate fatigue fracture and damage performance of asphalt mixtures. J Assoc Asphalt Paving Technol 2006;75:755–88.

[9] Kim YR, Seo Y, King M, Momen M. Dynamic modulus testing of asphalt concrete in indirect tension mode. Transport Res Rec 2004;1891:163–73.

[10] Bari J, Witczak MW. Development of a new revised version of the Witczak E* predictive model for hot mix asphalt mixtures. J Assoc Asphalt Paving Technol 2006;75:381–424.

[11] Wen H, Kim YR. Simple performance test for fatigue cracking and validation with WesTrack mixtures. Transport Res Board 2002;1789:66–72.

[12] Kim YR, Daniel JS, and Wen H. Fatigue performance evaluation of WesTrack asphalt mixtures using viscoelastic continuum damage approach. Research Report No. FHWA/NC/2002-004; 2002.

[13] Kim YR, Wen H. Fracture energy from indirect tension testing. J Assoc Asphalt Paving Technol 2002;71:779–93.

[14] Kim Y, Little DN, Lytton RL. Evaluation of microdamage, healing, and heat dissipation of asphalt mixtures using a dynamic mechanical analyzer. Transport Res Rec 2001;1767:60–6.

[15] Kim Y, Little DN, Lytton RL. Use of dynamic mechanical analysis (DMA) to evaluate the fatigue and healing potential of asphalt binders in sand asphalt mixtures. J Assoc Asphalt Paving Technol 2002;71:176–206.

[16] Kim Y, Little DN, Lytton RL. Fatigue and healing characterization of asphalt mixtures. J Mater Civ Eng 2003;15(1):75–83.

[17] Song I, Little DN, Masad E, Lytton RL. Comprehensive evaluation of damage in asphalt mastics using X-ray CT, continuum mechanics, and micromechanics. J Assoc Asphalt Paving Technol 2005;74:885–920.

[18] Masad E, Zollinger C, Bulut R, Little DN, Lytton RL. Characterization of HMA moisture damage using surface energy and fracture properties. J Assoc Asphalt Paving Technol 2006;75:713–54.

[19] Castelo BV, Masad E, Bhasin A, Little DN. Fatigue analysis of asphalt mixtures independent of mode of loading. Transport Res Rec 2008;2507:149–56.

[20] Ghuzlan KA, Carpenter SH. Energy-derived, damage-based failure criterion for fatigue testing. Transport Res Rec 2000;1723:141–49.

[21] Huang YH. Pavement analysis and design. 2nd ed. Englewood Cliffs, NJ: Prentice Hall; 2003.

[22] AASHTO TP 62-03. Determining dynamic modulus of hot-mix asphalt concrete mixtures. Provisional Standards; 2006.

[23] Lee HJ, Kim YR, Lee SW. Prediction of asphalt mix fatigue life with viscoelastic material properties. Transport Res Rec 2003;1832:139–47.

[24] Kim YR, Lee HJ, Little DN. Fatigue characterization of asphalt concrete using viscoelasticity and continuum damage theory. J Assoc Asphalt Paving Technol 1997;66:520–69.

[25] Lee HJ, Kim YR. A uniaxial viscoelastic constitutive model for asphalt concrete under cyclic loading. J Eng Mech 1998;124(11):1224–32.

[26] Lee HJ, Kim YR. A viscoelastic continuum damage model of asphalt concrete with healing. J Eng Mech 1998;124(11):1–9.