Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Characterizing Fatigue Behavior of Asphalt Mixtures Utilizing Loaded Wheel Tester

Hao Wu, Ph.D.[1]; Baoshan Huang, Ph.D., P.E., M.ASCE[2]; and Xiang Shu, Ph.D.[3]

[1] Associate Professor, Dept. of Road Engineering, School of Civil Engineering, Central South Univ., Changsha, 410075, P.R.China. Email: haoutk@gmail.com

[2] Associate Professor, Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996 (corresponding author). Email: bhuang@utk.edu

[3] Research Assistant Professor, Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996. Email: xshu@utk.edu

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Abstract:

Although widely used by state Departments of Transportation (DOTs) and other highway agencies for characterization of rut resistance and moisture susceptibility of asphalt mixtures, loaded wheel testers (LWTs) are rarely employed to evaluate the fatigue performance of asphalt mixtures, due to their inherent problems. In this study, LWT was used to characterize the fatigue behavior of asphalt mixtures. A commonly used type of LWT, Asphalt Pavement Analyzer (APA), was chosen as a platform and modified to conduct the fatigue testing. A linear variable differential transformer (LVDT) was mounted to the bottom of the specimen to measure the tensile strain on the bottom surface. The tensile stress was calculated by treating the test specimen as a simply-supported beam with a vertical load moving on its top. With the stress and strain measurements, theoretical analyses could be made to characterize the fatigue properties of asphalt mixtures. For comparison purpose, two other types of fatigue tests, beam fatigue and direct tension fatigue tests, were also conducted. Four types of asphalt mixtures were tested for their fatigue characteristics using the three fatigue tests. Two types of approaches−stiffness and dissipated energy−were adopted to analyze the fatigue behavior of asphalt mixtures. The results showed that LWT fatigue test was able to differentiate between asphalt mixtures in terms of fatigue behavior. The results from the LWT fatigue test were generally in consistent with those from flexural beam and direct tension fatigue tests. The LWT fatigue test has the potential to become a useful tool to rationally characterize fatigue properties of asphalt mixtures and to differentiate good-performing from poor-performing mixtures in terms of fatigue resistance.

Keywords: Loaded wheel tester (LWT); Fatigue; Laboratory testing, Performance

Accepted Manuscript Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Introduction

Fatigue cracking is one of the three major types of distress (rutting, fatigue cracking, and low temperature cracking) for asphalt pavements (Huang 1993). Fatigue resistance of an asphalt mixture is one of the major factors that pavement engineers need to consider for asphalt pavement design. Fatigue testing of asphalt mixtures involves subjecting asphalt mixture specimens to repeated loading either using a controlled stress or controlled strain. Currently, the commonly used fatigue tests for asphalt mixtures include flexural beam (four-point beam) fatigue test, semi-circular bending fatigue test, and direct or indirect tension fatigue test, and other types of fatigue tests (Shu et al. 2008; Wu 2011).

The flexural beam fatigue test, also called four-point beam bending test, is perhaps the most accepted fatigue test in the United States (Shu et al. 2008; Xiao et al 2009, 2011). It is a standard test method for determining the fatigue life of compacted Hot Mix Asphalt (HMA) subjected to repeated flexural bending (AASHTO 2005). It has been widely used for testing and evaluating the fatigue resistance of asphalt mixtures in the Strategic Highway Research Program (SHRP) Project A-003A (Hicks et al. 1993). In the test, a beam specimen is subjected to a repeated stress-controlled or strain-controlled load which is applied at the center of the beam until failure occurs. The beam specimen is placed in the fixture, which allows four-point bending with free rotation and horizontal translation at all loading and reaction points. Haversine loading is applied to the beam through the built-in digital servo-controlled pneumatic actuator, and the bending deflections can be measured by the LVDT mounted on the specimen. Usually, the failure of a test sample in a fatigue test is determined on the number of loading cycles, at which a 50 percent reduction in initial stiffness is reached (Hicks et al. 1993; Roberts et al. 1991;

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Williams 1998). The concept of pseudostiffness was proposed by Kim et al. (1995, 1997) and Lee (1996) in evaluating fatigue life of asphalt mixtures, and they reported that 50 percent reduction in pseudostiffness is an appropriate criterion indicting failure in the material.

Many researchers have investigated the fatigue characteristics of asphalt mixtures using the dissipated energy concept. Chomton and Valayer (1972) reported that the cumulative dissipated energy of an asphalt mixture is strongly related to its failure life and this relationship was independent of asphalt mixture type. Van Dijk (1975) and Van Dijk and Visser (1977) reported that there exist a strong relationship between the total dissipated energy and the number of loading cycles to failure and this relationship was not significantly affected by loading mode, frequency, temperature, and occurrence of rest periods, but was highly dependent on material type. Pronk and Hopman (1991) suggested that the dissipated energy per cycle or period was responsible for the fatigue damage in the asphalt mixtures. Tayebali et al. (1992) introduced two terms - “stiffness ratio” and “dissipated energy ratio” and found that there was a unique relationship between the stiffness ratio and the dissipated energy ratio, but not necessarily between cumulative dissipated energy and fatigue life. Baburamani and Porter (1996) showed a strong correlation between initial dissipated energy and fatigue life of asphalt mixtures.

More recent studies suggested that more consistent results can be achieved through the Ratio of Dissipated Energy Change (RDEC) (Ghuzlan and Carpenter 2000; Carpenter et al. 2003; Shen and Carpenter 2005, Shu et al. 2008). This concept was first introduced by Carpenter and Jansen (1997) who suggested using the change in dissipated energy to characterize the damage accumulation and fatigue life. The change in dissipated energy represents the total effect of fatigue damage without the necessity of considering material type and loading modes. The

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

application and study of RDEC were modified and expanded by Ghuzlan and Carpenter (2000), and then applied and verified by Carpenter et al. (2003).

Based on those studies, a Plateau Value (PV) which presents the nearly constant value of RDEC was proposed by Shen et al. (2006). This PV value represents a period where there is a constant percent of input energy being turned into damage during the fatigue process. The PV value is a function of the loading inputs for any mixture, and it varies with the mixture type for similar loading inputs. The PV value is significant because it provides a unique relationship with the fatigue life even for different mixtures, loading modes and loading levels (2006).

Nowadays, loaded wheel testers (LWTs), such as Asphalt Pavement Analyzer (APA), Hamburg wheel tracking device, and French LWT, are widely used to characterize the rut-resistance and moisture susceptibility of asphalt mixtures. However, they are seldom used to evaluate the fatigue cracking properties of asphalt mixtures due to some inherent problems. The present study explored the possibility of utilizing LWT for fatigue testing of asphalt mixtures with newly-developed strain measuring method (Wu 2011). Compared to other fatigue tests, the LWT fatigue test has the following advantages: (1) LWT is widely adopted and used by various highway agencies; (2) its testing condition is much closer to the actual loading situation of pavements (repetitive moving loads); (3) fabrication of specimens and test preparations are relatively simple and convenient; (4) multiple specimens can be tested simultaneously under dry or water submerged condition (Wu 2011).

Accepted Manuscript
Not Copyedited

Objective and Scope

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

The objective of the study is to utilize loaded-wheel tester (LWT) to develop a flexural bending fatigue test to characterize the fatigue behavior of asphalt mixtures. For comparison purpose, two types of fatigue tests, the beam fatigue test and direct tension fatigue tests were also carried out.

Four different asphalt mixtures made with two types of aggregates (limestone and granite) and three types of asphalt binder (PG 64-22, PG 70-22 and PG 76-22) were used for the characterization in this study.

Laboratory Fatigue Tests

Materials and Sample Preparation

Four asphalt mixtures typically used in the state of Tennessee were evaluated utilizing the LWT test in this study, as summarized in Table 1. Two types of aggregates (limestone and granite) and three types of asphalt binder (PG 64-22, PG 70-22, and PG 76-22) were used in the mixtures. An aggregate structure meeting Tennessee Department of Transportation (TDOT) specifications for 411-D mixtures was used as the design basis (TDOT 1995). Both limestone and granite had a nominal maximum aggregate size of 12.5 mm (1/2 in). The fine aggregates consisted of No.10 screenings, natural sand, manufactured sand, agricultural lime and screened RAP material (passing No. 4 sieve size, i.e., 4.75 mm). Ten percent RAP was used as substitutes for the fine aggregates in equal proportions for all the mixtures. The overall gradations of the mixtures were kept in a very narrow band so that all the mixtures had similar aggregate gradations (Huang et al. 2010). The optimum asphalt content was 5.0 percent (including asphalt from RAP) for the mixtures with limestone aggregates and 5.8 percent for the mixtures with granite aggregates.

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Two different methods were used for the compaction of specimens in this study. Beam specimens for flexural beam fatigue test were cut from the original specimens compacted by asphalt vibratory compactor (AVC). Cylindrical specimens for direct tension fatigue test were cored and trimmed from the original cylindrical specimens compacted by Superpave gyratory compactor (SGC). While the beam specimens for LWT fatigue test were compacted directly through AVC, and no trimming or coring process is needed. It should be noted that the LWT specimens were compacted to 5±1% air voids because the relative thin specimens made it hard to compact to 4±1% without damaging aggregate particles. Triplicate specimens were tested for each mixture in each fatigue test. The detailed information of specimens for the fatigue tests is provided in Table 2.

Fatigue Testing Methods

LWT Fatigue Test

The LWT fatigue test is intended to simulate the realistic conditions experienced by an asphalt mixture layer in the pavement. Its principal distinctive feature is that the cyclic loads are applied by means of the moving wheels. In the test, beam specimens were subjected to cyclic loads supplied by APA loading system, and the stress on bottom of the specimen was calculated according to the stress solutions (Wu 2011; Huang et al. 2012; Wu et al. 2012). Extensometers or LVDTs were installed on the specimens for measuring the tensile strains induced by the cyclic stresses (Fig. 1). Unlike the old version of APA fatigue test which uses the fracture of the test specimen or the metal wire attached to the bottom of the specimens as the failure criteria,

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

theoretical analysis approach can be applied to this new LWT fatigue test to analyze the fatigue behavior of asphalt mixtures utilizing the stress and strain measurements.

For stress analysis, the movement of the loading wheel on the test specimen can be simplified as a vertical load moving on a simply-supported beam (Wu 2011, Wu et al. 2012) (Fig. 2). Detailed information about the simplification and its verification can be found in Wu (2011) and Wu et al. (2012). The tensile stress, $\sigma(t)$, on the bottom and mid-span of the specimen can be expressed as (Wu 2011; Huang et al. 2012; Wu et al. 2012):

$$\sigma(t) = \frac{3Pl}{2bh^2} \cdot \sin^2\left(\frac{2\pi}{T} \cdot t\right) \quad (1)$$

where, P = wheel load, l = length of loading path, b = width of specimen, h = height of specimen, T = testing cycle period, and t = elapsed testing time.

With the calculated stress and the measured strain from the LVDT attached to the bottom of the specimen, the stiffness, hysteresis loop, dissipated energy, other parameters can be obtained to characterize the fatigue behavior of asphalt mixtures.

The LWT fatigue tests were performed at 10°C with 2Hz loading frequency in this study. The typical hysteresis loops with the change of loading cycles obtained from the tests are shown in Fig. 3. It can be seen clearly that the areas of the hysteresis loops were increasing with the increase of loading cycles.

Beam Fatigue Test

Copyright 2013 by the American Society of Civil Engineers

Accepted Manuscript
Not Copyedited

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

A strain level of approximately 600 microstrain and a loading frequency of 10 Hz were used such that the specimen will undergo a minimum of 10,000 load cycles. During each load cycle, beam deflections were measured at the center of the beam to calculate maximum tensile stress, maximum tensile strain, phase angle, stiffness, dissipated energy, and cumulative dissipated energy. The data were recorded automatically by a data acquisition system. Fig. 4 shows the beam fatigue test setup and the failure specimen after test.

Direct Tension Fatigue Test

The direct tension fatigue test provides a direct measurement of the fatigue behavior of asphalt mixtures under cyclic tensile loading. Before testing, specimens were placed in the environmental chamber at 10°C for at least two hours. During the test, specimen is suffered to a uniaxial repeated load which gives the specimen a relatively uniform tensile strain in its central section. Deformation over the central part of the specimen was monitored by means of three LVDTs attached to the glued-on studs (Fig. 5(a)). Once the stress and strain data have been obtained, the theoretical analysis for characterizing the fatigue behavior can be carried out. Fig. 5(b) illustrates the typical repeated sinusoidal loading and the corresponding response of the axial deformation recorded in the test. Table 3 presents the testing conditions of the three fatigue tests. Due to the differences in loading capacity of test equipment, specimen dimension, as well as stress and strain states the specimens subjected to, it was impossible to use the same testing condition for three different fatigue tests. Therefore, different testing conditions were applied for different fatigue tests. It should be pointed out that asphalt mixtures show different fatigue failure behavior in stress- and strain-controlled fatigue tests. However, due to the limitations in

Accepted Manuscript Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript Not Copyedited

applying load, flexural beam fatigue test was performed in the strain-controlled mode while direct tension and loaded wheel fatigue tests in stress-controlled mode.

Analysis Approaches

Stiffness Approach

The stiffness of asphalt mixtures decreases throughout the crack developing process in pavements. Generally, the stiffness vs. loading cycle plot of an asphalt mixture during fatigue testing exhibits three regimes of evolution, as shown in Fig. 6. In phase I, rapid decreases in stiffness can be observed, which followed by phase II which corresponds to a linear decrease in stiffness. While in phase III, fracture cracking will occur due to the damage acceleration of micro-cracks and ultimately turn to observable macro-cracks which will cause the failure of the specimen.

In this study, the commonly used 50% stiffness reduction method was adopted to determine the fatigue life of an asphalt mixture. This method defines the fatigue life of an asphalt mixture as the number of loading cycles when the stiffness decreases to 50% of its initial value measured at the 50th load cycle.

Dissipated Energy Approach

With the stress and strain measurements, a hysteresis loop can be constructed for an asphalt mixture subjected to fatigue testing (Fig. 7). The area of a hysteresis loop represents the energy

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

absorbed by the mixture. During the fatigue test, the change of the area of hysteresis loops indicates that part of the energy in the system has been dissipated, and some plastic strain or damage have occurred to the asphalt mixture. As loading cycles increase and cracks initiate and propagate the dissipated energy changes continuously throughout the fatigue process. Therefore, the concept of dissipated energy (DE) generated by an external work can be used as a direct and visualized way to describe the development of damage in asphalt mixtures. Dissipated Energy per cycle can be calculated by the stress σ_n, strain ε_n, and phase angle ϕ_n, $DE = \pi\sigma_n\varepsilon_n \sin\phi_n$. But the areas of the hysteresis loop are usually used for calculating the dissipated energy as the development of loading cycles.

In this strudy, the RDEC concept proposed by Carpenter et al (2003) was used to characterize the fatigue behavior of asphalt mixtures. RDEC is defined as follows:

$$RDEC = \frac{DE_{n+1} - DE_n}{DE_n} \tag{2}$$

where, *RDEC* = the ratio of dissipated energy change; DE_n = the dissipated energy in load cycle *n*; and DE_{n+1} = the dissipated energy in load cycle *n+1*.

Fig. 8 shows a typical plot of RDEC vs. loading cycles. The fatigue life can be characterized by a plateau value (PV) through the number of cycles at 50% reduction of initial stiffness (Shen 2006):

$$PV = \frac{1-\left(1+\frac{100}{Nf_{50}}\right)^{k}}{100} \tag{3}$$

Copyright 2013 by the American Society of Civil Engineers

where, k = coefficient; and Nf_{50} = number of loading cycles determined based on the 50% stiffness reduction.

According to Shen (2006), a unique relationship can always be established between PV and N_f regardless of the asphalt mixture type, loading mode and testing condition. Thus, the PV value method associated to RDEC was employed in this study to evaluate the fatigue life of asphalt mixtures.

Results and Discussion

Stiffness Approach

The results of the stiffness with respect to loading cycles are presented in Fig. 9. It is clear that all the three fatigue tests showed identical ranking order according to the stiffness results for various mixtures. The mixtures with higher asphalt binder grade exhibited higher initial stiffness and larger number of cycles to the rapid reduction of the stiffness. In addition, the stiffness vs. loading cycle curves from LWT fatigue tests in Fig. 9(c) can be well fitted by exponential functions. Although some non-coincident fittings are shown in the initial and tail parts of the curves, all of the R^2 of the fittings were greater than 0.97.

The results of the fatigue life (N_f) of the different mixtures are shown in Fig. 10. From the N_f results, mixture LS-3 showed longest fatigue life among all the mixtures, which followed by LS-2, GN-1 and LS-1. It indicates that higher grade asphalt binder had benefits on increasing the stiffness and crack resistance of asphalt mixtures. Although the initial stiffness of GN-1 was smallest among all the mixtures, with relatively higher asphalt content (5.8%) it exhibited longer

Accepted Manuscript
Not Copyedited

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

fatigue life than LS-1 (5.0%). It indicates that higher asphalt binder content had positive influence on the fatigue resistance of asphalt mixtures.

The results of fatigue life from the three fatigue tests were statistically compared using t-test with 5% level of significance and the p-values from the statistical analysis were presented in Table 4. It can be seen that like flexural beam and direct tension fatigue tests, the loaded wheel fatigue test could also differentiate between most of the asphalt mixtures used in the study.

RDEC Approach

Before dissipated energy results are used to calculate RDEC, the analysis range for the DE vs. loading cycle curve should be selected in order to minimize the error for the calculation, as shown in Fig. 11. A curve fitting process for this selected analysis range is required to obtain the most accurate fitting equation for the calculation of RDEC. For selecting this analysis range, some rules given in Shen (2006) should be complied with to reduce the subjective effects. In this study, the fitting functions with highest R^2 were chosen, and the exponents of the functions were used for the further calculations.

Once the exponent function from the curve fitting is obtained, RDECs can be calculated through a simplified formula proposed in Shen (2006). Plateau Value (PV) is defined as the value of RDEC when the number of the cycle is at the 50% reduction of stiffness (N_{f50}). It can be seen from Equation (3) that the PV is depending on both the change of dissipated energy and the change of stiffness. The lower PV usually represents a longer fatigue life, and vice versa.

Fig. 12 shows the results of PV from the different fatigue tests. It can be found that the PV results from LWT fatigue test were in good agreement with the results from flexural beam

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

and direct tension fatigue tests. The fatigue lives of various mixtures interpreted by PV were generally in consistent with those represented by N_{f50}. The mixtures with higher grade asphalt binder such as LS-3 and LS-2 exhibited lower PVs, which imply longer fatigue lives. The mixture with a higher asphalt content such as GN-1 showed a lower PV than Mixture LS-1, indicating that Mixture GN-1 would have a longer fatigue life than Mixture LS-1.

Table 5 presents the p-values from the statistical analysis on the PV results from the three fatigue tests. Except that there was no significant difference between mixtures GN-1 and LS-2, the loaded wheel fatigue test could show significant differences among other mixtures, indicating that it could differentiate between asphalt mixtures in terms of fatigue resistance.

The relationship between N_f and PV is plotted in Fig. 13. An apparent exponential relationship can be found between the N_f s and PVs. The similar relationship in form was also reported in Shen (2008) through a series fatigue tests, and it was said that this relationship is unique independent of mixture types. According to the results from this study, it seems that this unique relationship can be extended to the tests in different loading modes (controlled-stress or controlled-strain) and testing methods.

Summary and Conclusions

A testing method of using LWT to investigate the fatigue properties of asphalt mixtures is proposed in this study. LWT has its unique benefits for simulating the field situation that asphalt material suffered in the pavement. Thus, the test results are more reasonable to reflect the real fatigue behavior of asphalt mixtures. Based on the results from this study, the following can be summarized:

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

1. LWT fatigue tests were able to differentiate the differences between the fatigue resistances of various asphalt mixtures. The results from LWT fatigue tests were in consistent with those from flexural beam and direct tension fatigue tests. The results clearly indicated that the mixtures made with higher grade of asphalt binder showed higher initial stiffness and a longer fatigue life. The mixtures made with higher asphalt content exhibited lower initial stiffness but a longer fatigue life.
2. Compared to the old version of APA fatigue test, the modified test proposed in this study was more reasonable to characterize the fatigue behavior of asphalt mixtures. In this modified test, theoretical approaches for modeling the fatigue behavior of asphalt mixtures are able to be adopted once the stress and strain are known.
3. In the direct tension fatigue test, the direction of the pull load on the specimen is identical to the direction of the specimen's compaction. Thus, the pre-produced interlocking forces between aggregates created in the compaction process could resist a part of the load or absorb some energy during the test. However, in the LWT fatigue and flexural beam fatigue test, the direction of the tensile stress that the specimen suffered during the test is perpendicular to the direction of the compaction when the specimen was fabricated, which is similar to the situation in the field.
4. This study used APA as a platform to conduct the fatigue testing of asphalt mixtures. Similarly, other types of LWT also have the potential to be modified and updated for asphalt mixture fatigue testing.

References

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

AASHTO (2005). “Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending,” AASHTO T 321-03, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2B, American Association of State Highway and Transportation Officials, Washington D.C., 2005.

Baburamani, P.S. and Porter, D.W. “Dissipated Energy Approach to Fatigue Characterization of Asphalt Mixes”. Proceedings Combined 18th ARRB TR Conference Transit New Zealand Symposium, Christchurch, New Zealand, pp.327-347, 1996.

Carpenter, S.H., Ghuzlan, K., and Shen, S. “Fatigue Endurance Limit for Highway and Airport Pavements.” Transportation Research Record 1832, Transportation Research Board, Washington D. C., pp. 131-138, 2003.

Carpenter, S.H., and Jansen, M. “Fatigue Behavior under New Aircraft Loading Conditions.” Proceedings of Aircraft Pavement Technology in the Midst of Change, pp. 259-271, 1997.

Chomton, G., and Valayer, P.J. “Applied rheology of asphalt mixes, practical aspplications.” Proceeding of the 3th International Conference on the Structural Designing of Asphalt Pavements, London, Vol., p.214, 1972.

Ghuzlan, K, and Carpenter, S.H. “An Energy-Derived/Damage-Based Failure Criteria for Fatigue Testing.” Transportation Research Record 1723, Transportation Research Board, Washington D. C., pp. 141-149, 2000.

Hicks, R.G., Finn, F.N., Monismith, C.L., and Leahy, R. B. “Validation of SHRP binder specification through mix testing.” J. Assn. Asphalt Paving Technologists, 62, 565–614, 1993.

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Huang, B., Shu, X., and Wu, H. "Method and Apparatus for Fatigue and Viscoelastic Property Testing of Asphalt Mixtures using a Loaded Wheel Tester." U.S. Patent, Publication No. US2012/0253704A1, U.S. Patent and Trademark Office, 2012.

Huang, B., Shu, X., and Vukosavljevic, D. (2010). "Laboratory Investigation of Cracking Resistance of Hot-Mix Asphalt Field Mixtures Containing Screened Reclaimed Asphalt Pavement". Journal of Materials in Civil Engineering, 23(11), 1535-1543.

Huang, Y. H., Pavement Analysis and Design. Prentice Hall, Inc. Englewood Cliffs, New Jersey, 1993.

Kim, Y.R., Lee, H.J., and Little, D.N. "Fatigue characterization of asphalt concrete using viscoelasticity and continuum damage theory." Journal of Association of Asphalt Paving Technologists, Vol.66, pp.520–569, 1997.

Kim, Y.R., Lee, Y.C., and Lee, H.J. "Correspondence principle for characterization of asphalt concrete." Journal of Materials of Civil Engineering, 7(1), 59–68, 1995.

Lee, H.J. "Uniaxial constitutive modeling of asphalt concrete using viscoelasticity and continuum damage theory." PhD thesis, North Carolina State University, Raleigh, N.C., 1996.

Pronk, A.C. and Hopman, P. C. "Energy Dissipation: The Leading Factor of Fatigue". Highway Research: Sharing the Benefits (J. Porter, ed.), London, 1991.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y., and Kennedy, T.W. "Hot Mix Asphalt Materials, Mixture Design, and Construction." 2nd Edition, NAPA Education Foundation, Lanham, Maryland, 1991.

Shen, S. "Dissipated energy concepts for HMA performance: Fatigue and healing". Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL., 2006.

Copyright 2013 by the American Society of Civil Engineers

Shen, S., Airey, G.D., Carpenter, S.H. and Huang, H. "A Dissipated Energy Approach to Fatigue Evaluation." International Journal of Road Materials and Pavement Design, Vol. 7, Issue 1, 2006.

Shen, S., and Carpenter, S.H. "Application of Dissipated Energy Concept in Fatigue Endurance Limit Testing." Transportation Research Record, Issue:1929: 165- 173, 2005.

Shu, X., Huang, B., and Vukosavljevic, D. (2008). "Laboratory evaluation of fatigue characteristics of recycled asphalt mixture." Constr. Build. Mater., 22(7), 1323–1330.

Tayebali, A.A., Rowe, G.M., and Sousa, J.B. "Fatigue Response of Asphalt Aggregate Mixtures." Proceedings of Asphalt Paving Technologists, Vol.62, pp.385-421, 1992.

TDOT. Standard specification for road and bridge construction. Tennessee Department of Transportation, Nashville, TN, March, 1995.

Van Dijk, W. "Practical Fatigue Characterization of Bituminous Mixes." Proceedings of the Association of Asphalt Paving Technologists (AAPT), Vol.44, pp. 38, 1975.

Van Dijk, W., and Visser, W. "The Energy Approach to Fatigue for Pavement Design." Proceedings of Annual meeting of the Association of Asphalt Paving Technologists (AAPT), Vol.46, pp.1-40, 1977.

Williams, D.A. "Microdamage healing in asphalt concretes: relating binder composition and surface energy to healing rate." PhD thesis, Texas A&M University, 1998.

Wu, H., Investigating properties of pavement materials utilizing loaded wheel tester (LWT), Ph.D. dissertation, University of Tennessee, Knoxville, Tennessee, USA, 2011.

Wu, H., Huang, B., and Shu, X. "Characterizing Viscoelastic Properties of Asphalt Mixtures Utilizing Loaded Wheel Tester (LWT)," Road Materials and Pavement Design, Vol. 13, No. S1, 38–55, 2012.

Accepted Manuscript
Not Copyedited

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Copyright 2013 by the American Society of Civil Engineers

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Xiao F., Amirkhanian S.N., and Wu B., “Fatigue and Stiffness Evaluations of Reclaimed Asphalt Pavement in Hot Mix Asphalt Mixtures”, Journal of Testing and Evaluation (ASTM), Vol. 39, No.1, pp. 50-58, 2011.

Xiao, F., Zhao, W., and Amirkhanian, S.N., “Fatigue Behavior of Warm Asphalt Mixture Containing CRM Binder”, Construction and Building Materials Vol.23, No.10, pp.3144-3151, 2009.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

LIST OF TABLES

LIST OF FIGURES

Accepted Manuscript
Not Copyedited

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Copyright 2013 by the American Society of Civil Engineers

Figure 1

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

(a) Test setup

(b) Specimen after test

Fig. 1. LWT Fatigue Test

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

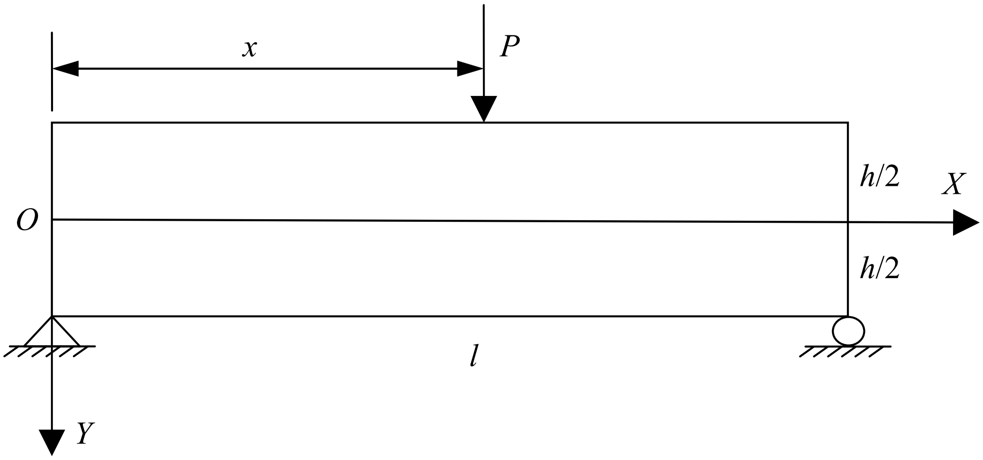


Fig. 2. Simplified Mechanical Model for Stress Analysis

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 3

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

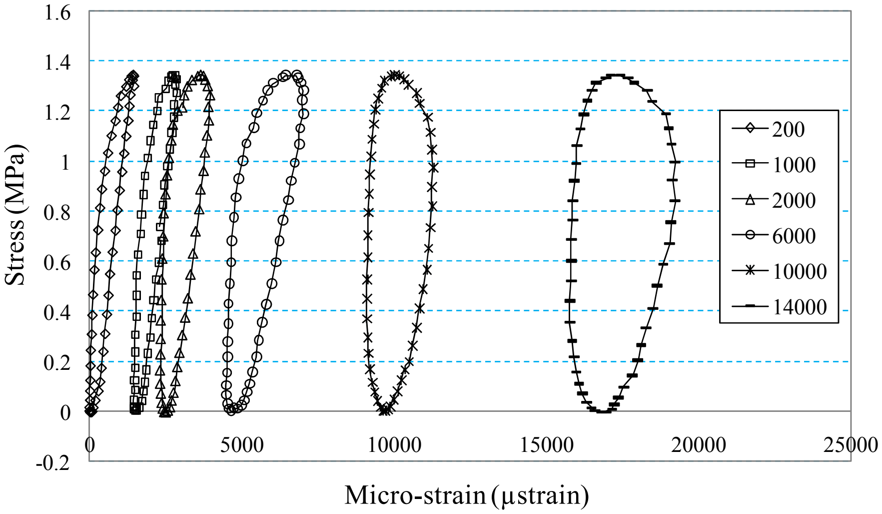


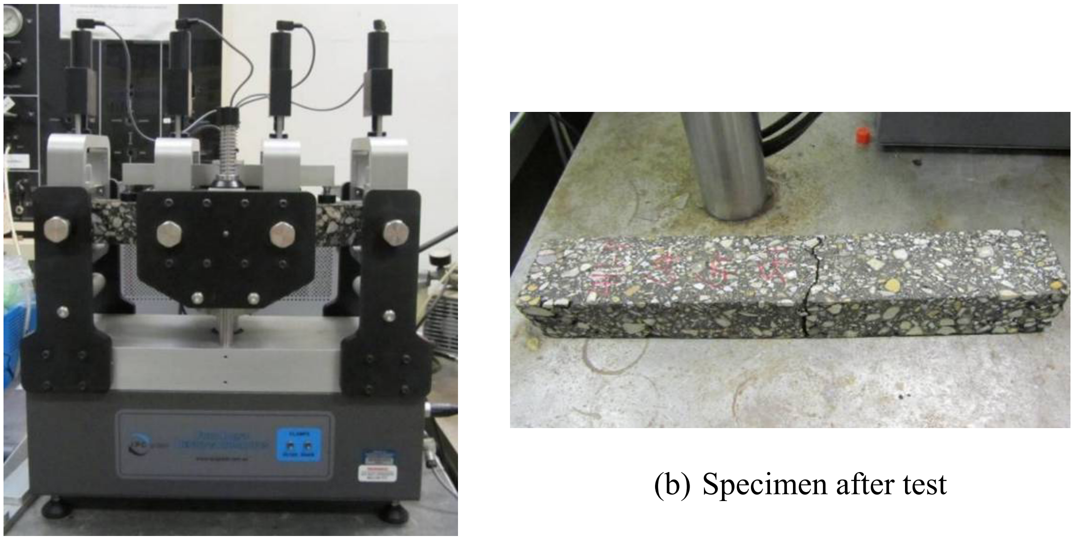
Fig. 3. Typical Hsteresis Loops with the Change of Load Cycles from LWT Fatigue Test

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.



(a) Testing device

(b) Specimen after test

Fig. 4. Beam Fatigue Test

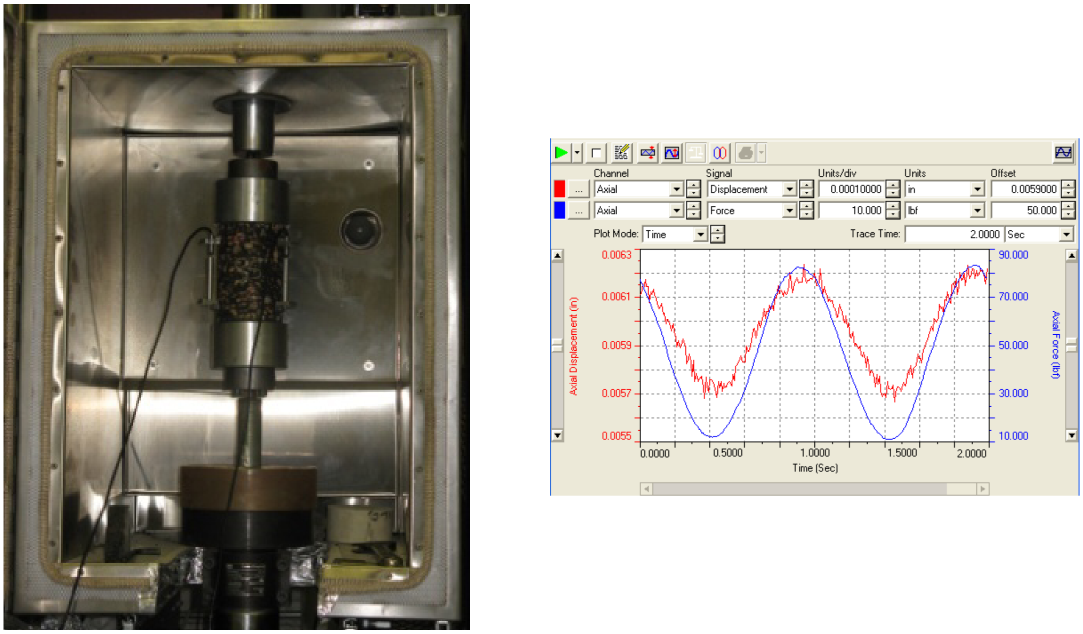
Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 5

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.



	Channel	Signal	Units/div	Units	Offset
🟥	Axial	Displacement	0.00010000	in	0.0059000
🟦	Axial	Force	10.000	lbf	50.000

Plot Mode: Time

Trace Time: 2.0000 Sec

(a) Test setup (b) Raw data from the test

Fig. 5. Direct Tension Fatigue Test

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 6

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

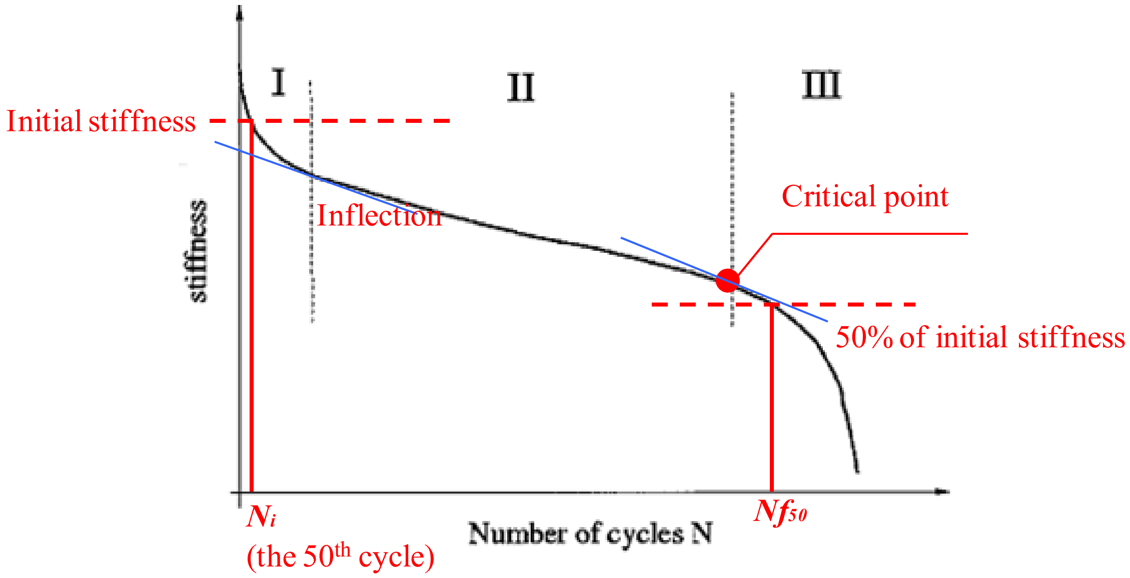


Fig. 6. Typical Stiffness vs. Loading Cycle Plot in Fatigue Test

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

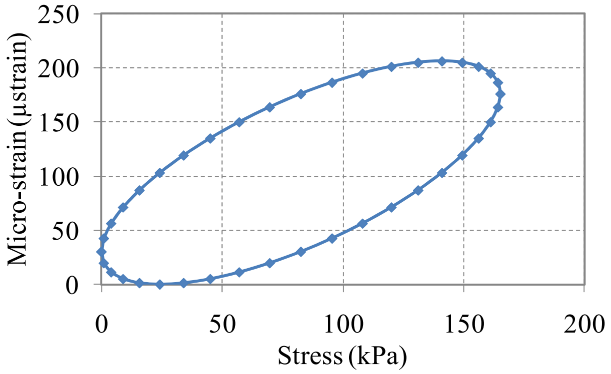


Fig. 7. Typical Stress-Strain Hysteresis Loop

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 8

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

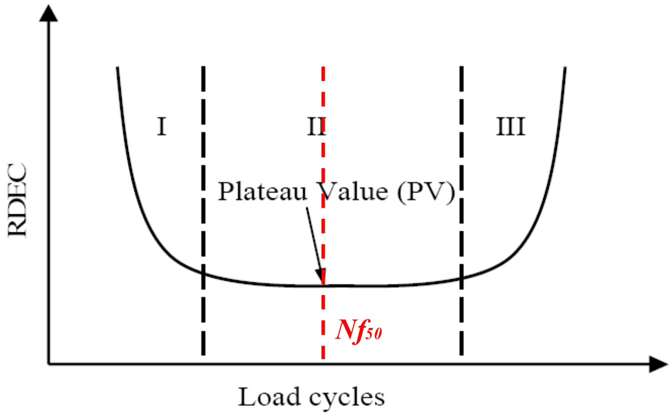


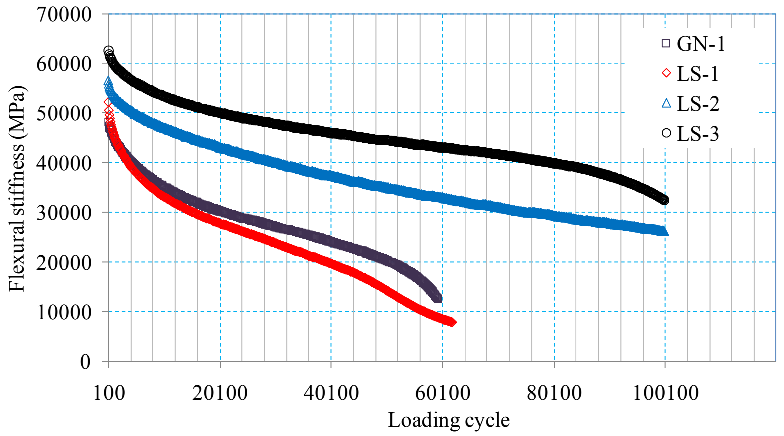
Fig. 8. Typical RDEC vs. Load Cycle Curve

Accepted Manuscript
Not Copyedited

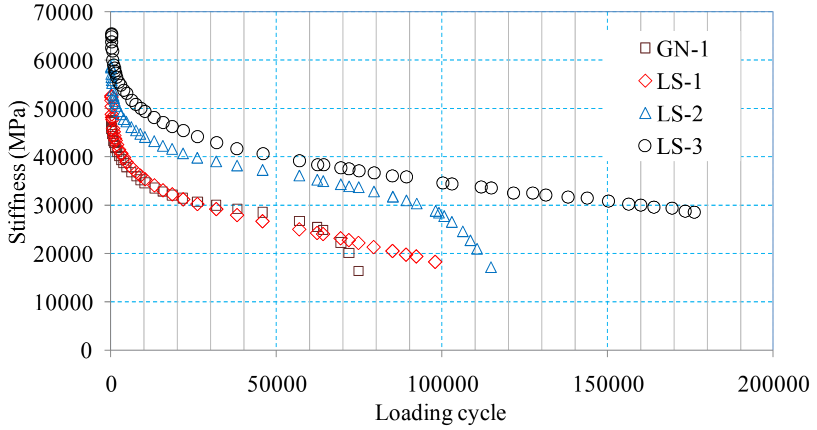
Copyright 2013 by the American Society of Civil Engineers

Figure 9

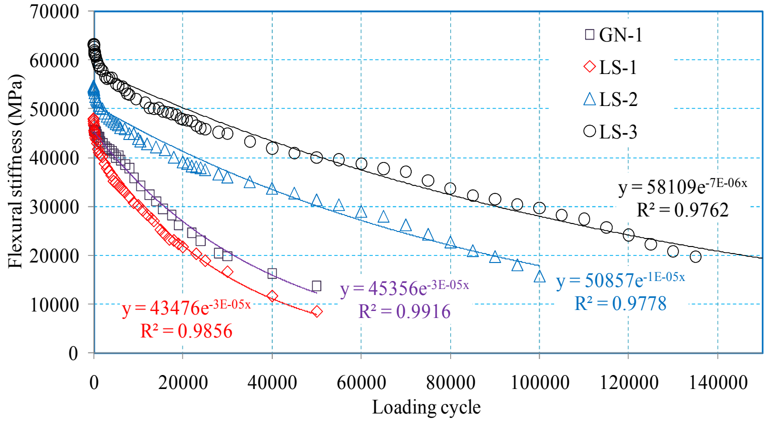
Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791



(a) Flexural beam fatigue test



(b) Direct tension fatigue test



(c) LWT fatigue test

Fig. 9. Stiffness vs. Loading Cycle Plots from Different Fatigue Tests

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 10

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

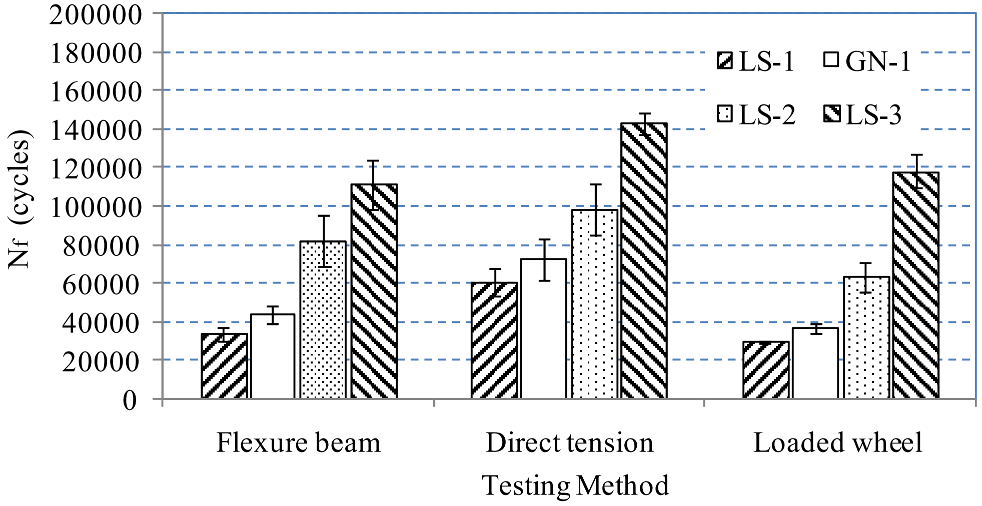


Fig. 10. N_f Results of Different Mixtures from Three Fatigue Tests

Accepted Manuscript
Not Copyedited

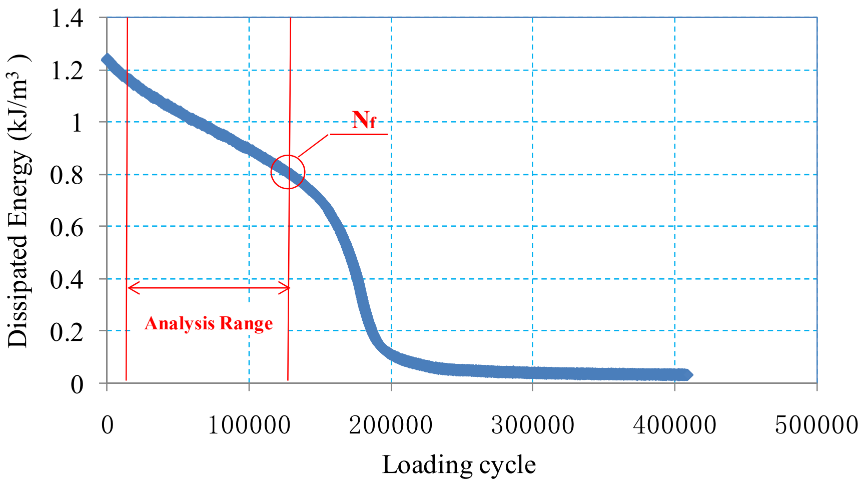
Copyright 2013 by the American Society of Civil Engineers

Figure 11

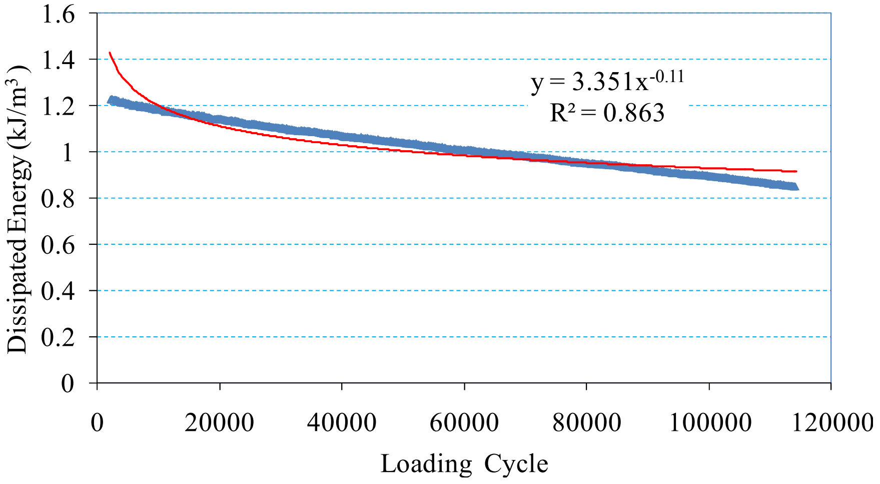
Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited



(a) Dissipated energy vs. loading cycle



(b) Exponential curve fitting

Fig. 11. Curve Fitting Process for Dissipated Energy vs. Loading Cycle

Copyright 2013 by the American Society of Civil Engineers

Figure 12

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

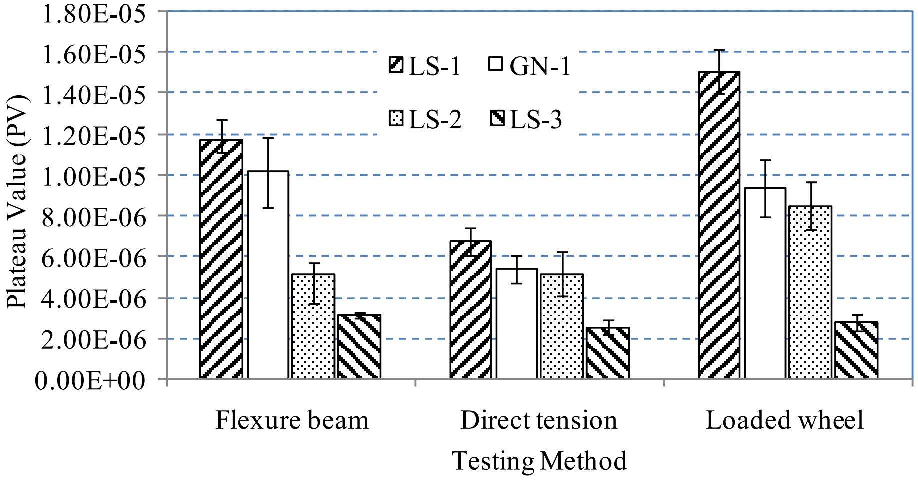


Fig. 12. PV results of Different Mixtures from Three Fatigue Tests

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Figure 13

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013; posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

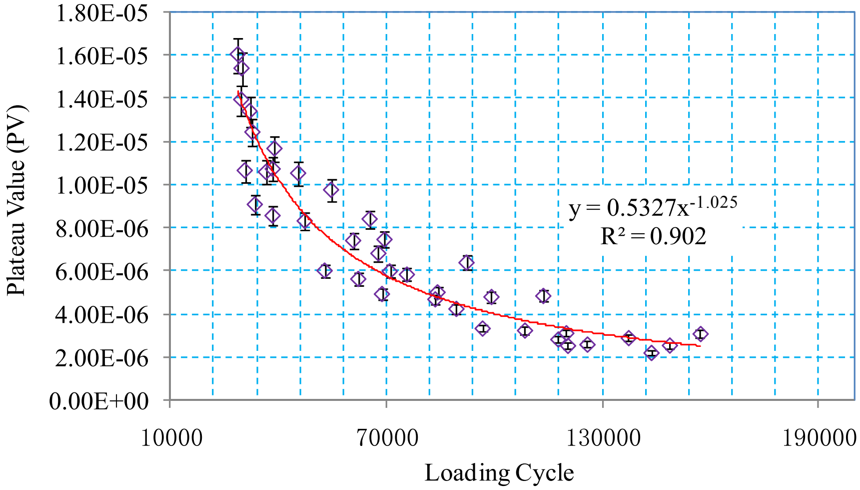


Fig. 13. Relationship between PV and N_f

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Table 1. Asphalt Mixtures

Mixture	**Aggregate**	**Asphalt binder**	**Asphalt content**
GN-1	Granite	PG 64-22	5.8%
LS-1	Limestone	PG 64-22	5.0%
LS-2	Limestone	PG 70-22	5.0%
LS-3	Limestone	PG 76-22	5.0%

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Table 2. Specimens for Fatigue Tests

Test	**Specimen Type**	**Compaction Method**	**Air Voids (%)**
LWT	300*125*50mm beam	Asphalt Vibratory Compactor (AVC)	5±1
Flexural beam	380*50*63mm beam	Asphalt Vibratory Compactor (AVC)	4±1
Direct tension	100*150mm cylinder	Superpave Gyratory Compactor (SGC)	4±1

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers

Journal of Materials in Civil Engineering. Submitted November 7, 2012; January 29, 2013;
posted ahead of print January 31, 2013. doi:10.1061/(ASCE)MT.1943-5533.0000791

Table 3. Testing Condition for Thee Fatigue Tests

Fatigue Test	Test Temperature	Loading Frequency	Strain/Stress Level	Test Equipment
Flexural Beam	10 ºC	10 Hz	$600 x 10^{-6}$	Beam Fatigue Apparatus
Uniaxial Tension	10 ºC	2 Hz	382 kPa	Material Testing System (MTS)
Loaded Wheel	10 ºC	2 Hz	1132 kPa	Asphalt Pavement Analyzer (APA)

Downloaded from ascelibrary.org by Tennessee, University Of on 08/27/13. Copyright ASCE. For personal use only; all rights reserved.

Accepted Manuscript
Not Copyedited

Copyright 2013 by the American Society of Civil Engineers