Influence of self-heating and nonlinearity on asphalt mixture recovery properties

Ivan Isailović, Michael P. Wistuba and Augusto Cannone Falchetto
(Technische Universität Braunschweig, Department of Civil Engineering, ISBS - Pavement Engineering Centre, Beethovenstraße 51 b, 38106, Braunschweig, Germany; i.isailovic@tu-bs.de)

ABSTRACT

The recovery potential of asphalt mixture is experimentally investigated with cyclic loading tests presenting rest period of different durations, from 500 seconds to 86400 seconds, and by taking into consideration nonlinearity and self-heating effects. For this purpose, discontinuous fatigue (recovery) tests and temperature sweep tests are performed using the uniaxial tension-compression stress-controlled testing mode. In order to monitor the temperature variation inside the specimen during cyclic loading, a small temperature sensor is embedded in the middle portion of the sample during compaction. Depending on the rest period duration, the effects of nonlinearity and self-heating can significantly influence the asphalt mixture recovery properties. The nonlinearity effect is especially pronounced for very short rest periods and decreases as the time for the rest increases. On the other hand, the effect of the temperature variation in the core of the specimen increases until rest period duration of approximately 2000 seconds, thereafter a continuous decrease is observed. For the specific asphalt mixture used in this research, the 2000 seconds rest period duration represents a limit beyond which the self-heating effect does not further affect the complex modulus recovery.

Keywords: asphalt mixture recovery, self-heating, nonlinearity

1. INTRODUCTION

Heavy traffic and climate loading induce a repeated and cyclic state of stress in asphalt pavements. As pavement structures are not continuously loaded, the rest periods between each traffic loading repetition may induce a recovery of the material mechanical properties and lead to the partial or complete reversibility of progressive micro fatigue cracking effects. This phenomenon is commonly known as self-healing. Self-healing is defined as the materials recovery capability under certain loading and environmental conditions, especially during rest periods [1]. It is assumed that the self-healing potential extends the durability of asphalt pavements since asphalt materials with high recovery capabilities accumulate less deformation and less damage in the asphalt layers [2].

For addressing the self-healing and fatigue properties of asphalt mixtures, cyclic laboratory tests on asphalt mixture specimens with and without application of rest period are usually performed, respectively [3]-[4]. Usually, the damage and self-healing properties in these tests are related to the complex modulus evolution.

Since laboratory cyclic excitation does not completely simulate the "in situ" loading conditions, some biasing effects can appear together with fatigue and self-healing, such as nonlinearity, self-heating, thixotropy and strain relaxation (for stress-controlled tests) [5]. These effects show highly asphalt mixture composition dependency, and can significantly affect the complex modulus evolution during cyclic laboratory tests [6], [7]. Due to the complete reversibility during the rest period, they cannot be accounted for self-healing and have to be separately considered. If observed together the term material recovery should be used.

The objective of this work is to investigate the recovery properties of a hot mix asphalt mixture, where effects of nonlinearity and self-heating are considered. For this purpose, discontinuous fatigue tests with single rest periods of different duration and temperature sweep tests are performed.

2. EXPERIMENTAL STUDY

2.1. Material and fabrication of asphalt mixture specimens

In this experimental study asphalt mixture for surface courses, AC 11, was prepared (Asphalt Concrete - AC, maximum grain size of 11 mm, 5.6 mass-% of plain asphalt binder 50/70). Asphalt mixture slabs having dimensions 320 x 200 x 50 mm³ were prepared using segmented steel roller compaction method [8].

For the determination of the temperature variation inside the specimen during cyclic loading, a temperature sensor PT100 was embedded in the middle part of the sample during compaction (see FIGURE 1). Due to its relatively small size and to the robustness given by the ceramic housing, a good integration of the sensors in the asphalt mixture is guaranteed. This procedure avoids the introduction of a point of weakness in the specimen, which is usually the case when the sensor is placed after compaction by drilling a hole in the specimen. The present solution consistently limits the distortion of the stress field and while preserving a better material continuity in the specimen.

From the slabs, prismatic specimens were cut with final dimensions of 50 x 50 x 160 mm³ and having average air voids contents of 5.5 %.

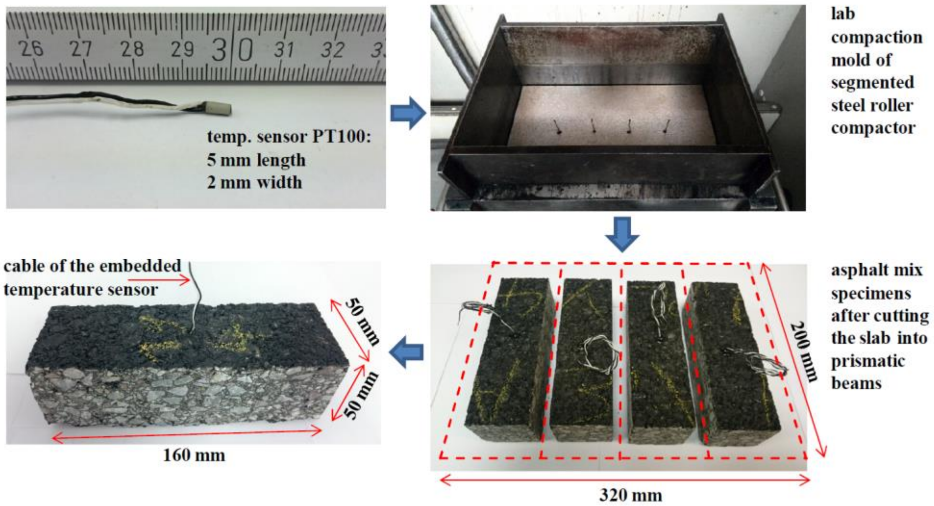

FIGURE 1 Procedure for placing the temperature sensor PT100 for temperature monitoring inside the asphalt specimen.

2.2. Test procedure

The asphalt mixture recovery properties were evaluated using uniaxial stress-controlled tension-compression test apparatus. During the test, a vertical stress amplitude is applied, and the resulting deformation is measured using two analog strain transducers, attached to both sides of the test specimen. In total, two types of test modes were performed:

- temperature sweep test, and
- discontinuous fatigue test with single rest period of different duration (recovery test).

Temperature sweep test was employed in order to determine the viscoelastic properties and the complex modulus-temperature dependence of the selected asphalt mixture. In this test, a short loading sequence of 50 loading cycles with 0.7 MPa stress amplitude is applied at the following temperatures: 15, 17.5, 20, 22.5, and 25 °C. The test starts at 15 °C and ends at 25 °C, with 7200 seconds of conditioning time between each temperature. Based on these results, the influence of self-heating on the complex modulus evolution effect can be quantified.

The evaluation of the recovery properties was achieved using discontinuous fatigue test. The single rest period was introduced when the asphalt sample experienced 36 % decay of the initial complex modulus (loading phase 1, cp. FIGURE 3). During the rest period, the asphalt sample was in a stress-free condition. After the rest period, the specimen was loaded with a new loading sequence till failure (loading phase 2, cp. FIGURE 3). The recovery tests were performed at a stress amplitude of 0.7 MPa and at a temperature of 20 °C. Several rest period durations were imposed, from 500 seconds up to the 86400 seconds, with three test replicates.

3. EXPERIMENTAL RESULTS

3.1. Temperature sweep test

The absolute value of complex modulus at each temperature (cp FIGURE 2) was calculated as the mean value from cycles 40 to 50, showing a linear trend for the considered temperature range and stress amplitude of 0.7 MPa. This was also observed earlier by Di Benedetto et al. [6] at small strain amplitudes in strain-controlled mode.

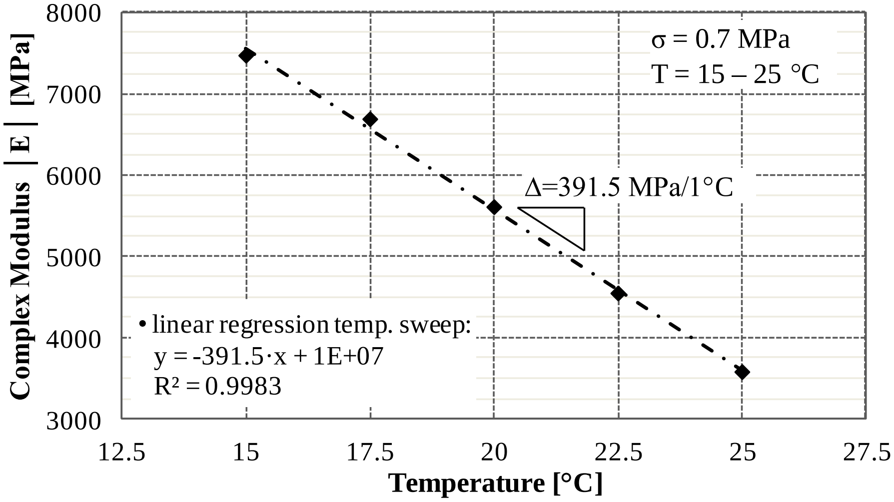

FIGURE 2 Evolution of the absolute value of complex modulus in function of temperature at the stress amplitude of 0.7 MPa in temperature sweep test.

Based on the linear regression, relative change of the absolute value of complex modulus per one-degree temperature decrease is calculated (Δ=385.88 MPa/1°C). This value was subsequently used for the quantitative estimation of the self-heating effect on complex modulus evolution in recovery tests at a stress amplitude of 0.7 MPa and at a temperature of 20 °C.

3.2. Recovery test

FIGURE 3 (left) shows the evolution of the complex modulus in one recovery test with a rest period of 86400 seconds. The total complex modulus recovery is calculated as the difference between values at the beginning of the loading phase 2 (first cycle) and the end of the loading phase 1 (last cycle). A relatively high recovery of the complex modulus is observed during the rest period which is close to the one at the beginning of the first loading phase.

In almost all tests the development of the macro-crack was not experienced across the placement point of the temperature sensor, confirming the good experimental practice followed during the preparation of the asphalt mixture specimens.

The Recovery capability determined on the asphalt mixture is highly dependent on the duration of the rest period, and it increases as the time for material recovery increases (cp. FIGURE 3, right). Beyond a certain rest period duration (in this case ca. 20000 seconds) there is no influence on recovery of asphalt mixture and a plateau stage is reached. As previously stated, this recovery cannot be attributed to self-healing phenomena only.

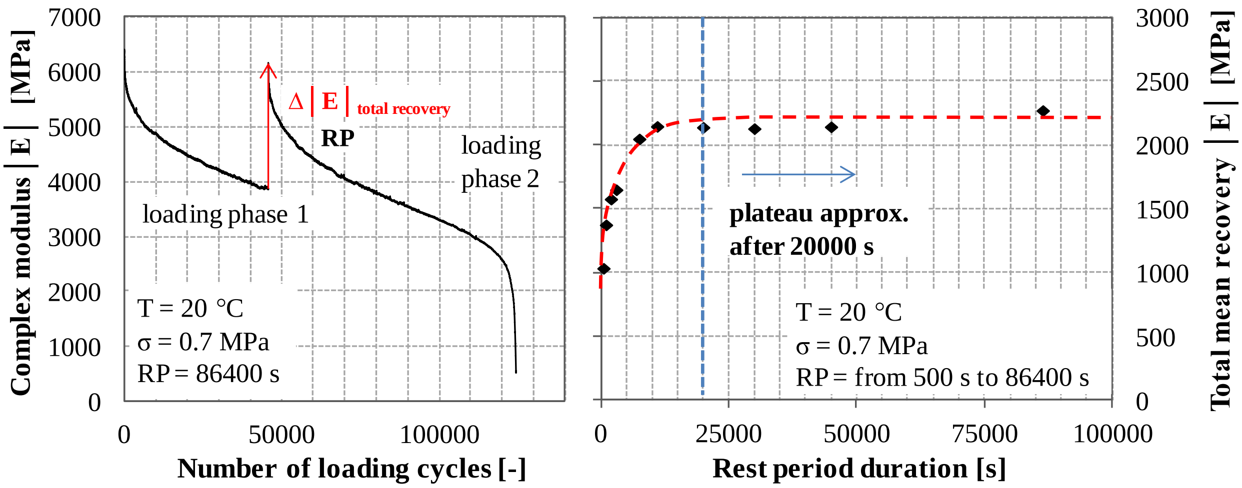

FIGURE 3 Evolution of the absolute value of complex modulus in function of the number of loading cycles in the recovery test with a rest period of 86400 seconds (left), and mean recovery of the absolute value of complex modulus for different rest period durations (right).

The nonlinearity effect, which contributes to the complex modulus recovery during the rest period, is observed at the beginning of the cyclic loading. This effect disappears as soon as a specified stress amplitude is achieved. FIGURE 4 (left) shows a magnified representation of FIGURE 3 (left), where a rest period of 86400 seconds was imposed. Since stress amplitude of 0.70 MPa was not achieved immediately, the complex modulus shows a decay resulting from non-linear viscoelastic asphalt properties. This complex modulus decay is referred to the effect of nonlinearity only since the influence of other effects in this initial phase is assumed to be negligible. Therefore, the nonlinearity effect $\Delta|E|_{nonlinearity}$ can be calculated as the difference between the first value of complex modulus in the loading phase 2 and the complex modulus at cycle 31, where the stress amplitude of 0.7 MPa was achieved (cp. FIGURE 4, left).

By calculating the effect of nonlinearity (in percent) on total complex modulus recovery for all rest period durations considered (cp. FIGURE 4, right), it can be seen that the nonlinearity effect shows the highest influence when rest period duration is low. This is a consequence of the relatively steady recovery of complex modulus due to the nonlinearity effect (in MPa) for all rest period durations considered.

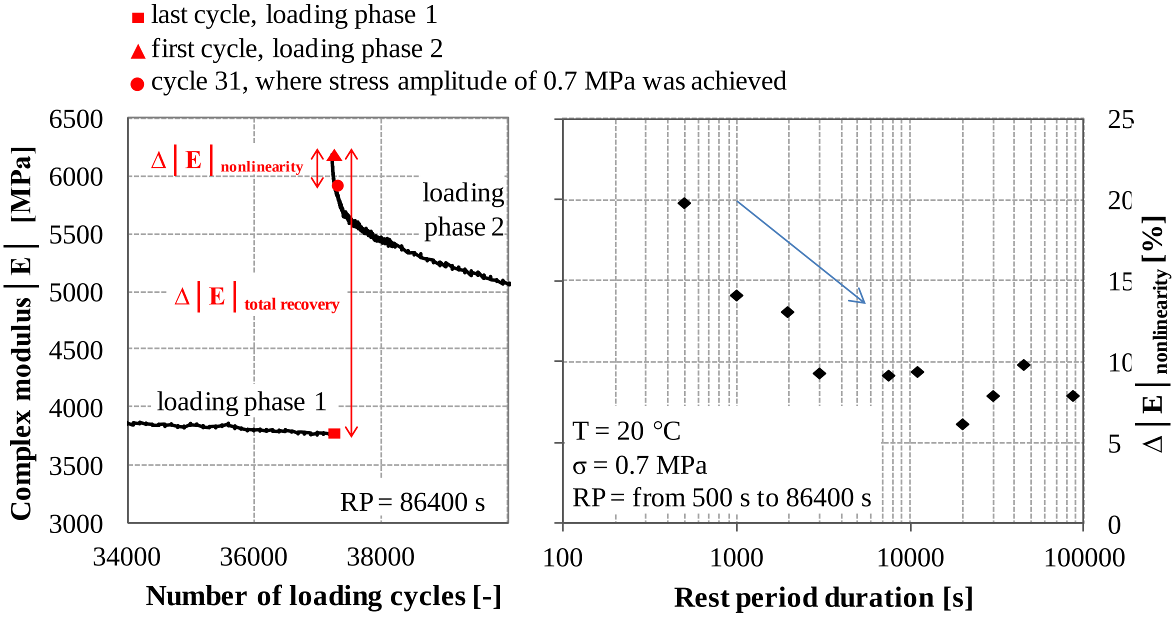

FIGURE 4 Close look representation of complex modulus evolution in recovery test with rest period duration of 86400 seconds (left), and effect of nonlinearity (in percent) on total complex modulus recovery over various rest period durations (right).

The influence of self-heating on complex modulus recovery was determined based on the temperature change recorded through an embedded sensor in the core of the specimen. FIGURE 5 (left) shows the variation of the specimen temperature in loading phase 1 and during the rest period of one recovery test. A significant temperature increase, caused by the dissipated viscous energy [6], can be observed in the loading phase 1. Based on stress-free conditions during the rest period, the temperature is continuously reduced down to the initial value imposed at the beginning of the test (equal to thermal chamber temperature). Based on the core temperature change and the results from temperature sweep test, the influence of the self-heating on complex modulus recovery can be determined as shown in FIGURE 5 (left).

By calculating the effect of self-heating (in percent) on total complex modulus recovery for all rest period durations considered (cp. FIGURE 4, right), it can be seen that the self-heating effect increases until rest period duration of approximately 2000 seconds, thereafter a continuous decrease is observed. For the specific asphalt mixture used in this research, the 2000 seconds rest period duration represents a limit beyond which the self-heating effect does not further affect the complex modulus recovery. The temperature of the specimen reaches the equilibrium (or envirmonemtnal chamber temperature) approximately after 2000 seconds.

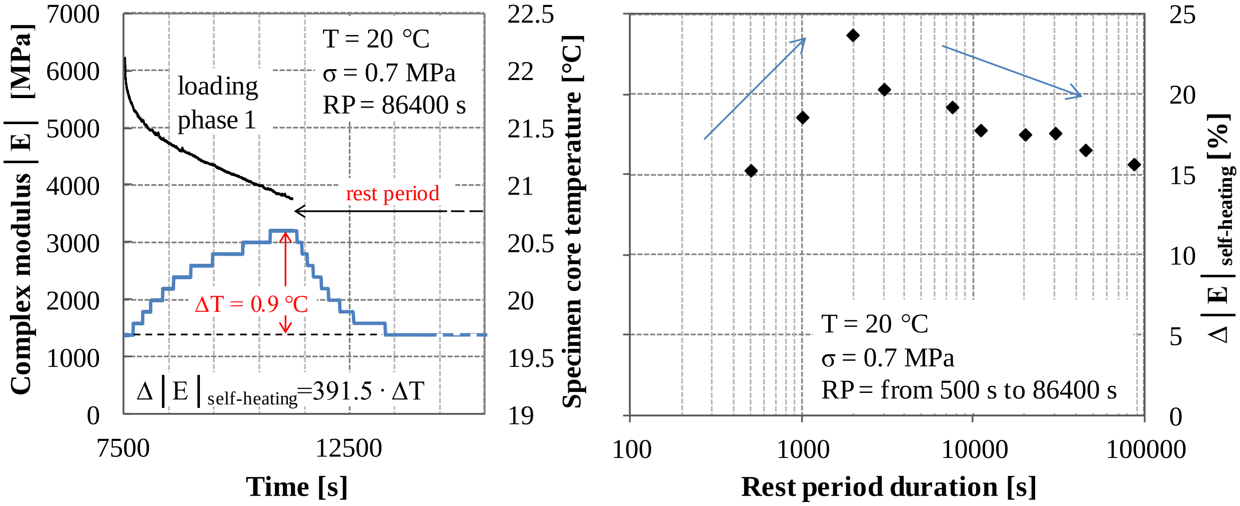

FIGURE 5 Time evolutions of absolute values of complex modulus and specimen core temperatures in recovery test with a rest period of 86400 seconds (left), and effect of self-heating (in percent) on total complex modulus recovery over various rest period durations (right).

4. CONCLUSIONS

In this study, the recovery potential of asphalt mixture is experimentally investigated using cyclic uniaxial stress-controlled tension-compression tests. Two types of test mode were applied: (i.) discontinuous fatigue tests with single rest periods of different durations from 500 seconds to 86400 seconds, and (ii.) temperature sweep tests. The rest period duration dependency was studied taking into consideration nonlinearity and self-heating effects observed during cyclic loading.

For monitoring of the temperature variation inside the specimen during cyclic loading, a small temperature sensor was embedded in the middle part of the sample during compaction. This procedure minimally affects the stress field in the specimen.

Based on the test results, the following conclusions can be drawn:

- The effect of nonlinearity contributes up to the 20 % to the total recovery. This effect is especially pronounced at very short rest periods and decreases as the time for the rest increases.
- The effect of self-heating increases until rest period duration of roughly 2000 seconds, thereafter a continuous decrease is observed. For the specific asphalt mixture used in this research, the 2000 seconds rest period duration represents a limit beyond which the self-heating effect does not further affect the complex modulus recovery. At this rest period duration, the influence of self-heating on total recovery reaches its highest value (24 %).

These findings are based on investigations of one asphalt mixture type only and may be vary depending on material type.

5. REFERENCES

[1] Shen S, Chiu H, Huang. Fatigue and healing in asphalt binders. CD-ROM. Transportation Research Board Meeting, Washington, D.C, 2009.

[2] Luo X, Luo R, Lytton, L. Characterization of recovery properties of asphalt mixtures. Construction and Building Materials 48, pp. 610-621, 2013.

[3] Breysse D, De LA Roche C, Domec V, Chauvin J.J. Influence of rest time on recovery and damage during fatigue tests on bituminous composites. Proc. of 6th RILEM Symposium Performance Testing and Evaluation of Bituminous Materials PTEBM, pp. 416-423, Zürich, 2003.

[4] Carpenter S, Shen, S. A dissipated energy approach to study hma healing in fatigue. In Transportation Research Record (TRR): Journal of the Transportation Research Board, No 1970, pp. 178-185, 2006.

[5] Lundström R, Ekblad J, Isacsson U. Influence of hysteretic heating on asphalt fatigue characterization. Journal of testing and Evaluation, Vol. 32 No. 6, 2004.

[6] Di Benedetto H, Nguyen Q-T, Sauzéat C. Nonlinearity, heating, fatigue and thixotropy during cyclic loading of asphalt mixtures. Road Materials and Pavement Design, 12(1):129-158, 2012.

[7] Mangiafico S, Sauzéat C, Di Benedetto H, Pouget F, Planque L. Quantification of biasing effects during fatigue tests on asphalt mixes: non-linearity, self-heating and thixotropy. Road Materials and Pavement Design, Volume 16, pp. 73-99, 2015.

[8] Wistuba, M. The German segmented steel roller compaction method – state-of-the-art report. Int. Journal of Pavement Engineering, Vol. 17, pp. 81-86, 2014.