Quantification of Self-Healing in Warm Mix Asphalt Binders using Linear Amplitude Sweep Test

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ABSTRACT: Incorporating asphalt's self-healing properties into experimental protocols can help bridge the gap between laboratory predictions and the actual field performance of asphalt mixes in terms of fatigue life. In this study, the healing potential of an unmodified binder is quantified both in the presence and absence of a warm mix additive (WMA). During the test, rest periods of varied durations (10 and 30 minutes) are introduced at 25% and 75% of damage levels prior to reaching failure to examine their influence on the further evolution of damage. It was observed that the addition of the WMA resulted in an improved healing index of the unmodified binder at different damage levels pre-failure. The findings indicate that WMA additives not only help reduce working temperatures but also improve the healing properties of bituminous mixes.

1 INTRODUCTION

Significant energy consumption is involved during the production of bituminous mixtures mainly from oil refineries and asphalt mixing plants, making it the second most energy-intensive industry (Zapata & Gambatese, 2005). Higher bitumen production temperatures result in considerable energy demand for heating aggregates and binders, leading to high greenhouse gas emissions. By lowering production and compaction temperatures by 30 to 50°C compared to conventional hot mix asphalt (HMA), WMA not only reduces emissions but also improves workability, minimizes aging and facilitates cold weather paving (Milad et al., 2022).

Fatigue cracking is one of the major modes of distress in bituminous pavements (IRC 37, 2018). The healing potential of asphalt mixtures refers to their ability to repair cracks during rest periods between traffic loads. Self-healing is a process by which the micro-cracks caused due to the traffic gradually close and restore the material's properties without external intervention (Pronk, 1997; Wang et al., 2018). This results in improved stiffness and fatigue resistance in the pavement.

Discrepancies between laboratory-based predictions and field performance of bituminous mixes generally happen due to various reasons such as differences in loading mode, moisture susceptibility, environmental conditions and construction aspects. One critical reason for the underestimation of fatigue life in laboratory settings is the failure to incorporate the self-healing properties of asphalt binders. Introducing a rest period during the fatigue test has been found to expedite damage recovery in bituminous material (Xie et al., 2017). This also replicates the intermittent loading conditions experienced in the field and thus better captures the stiffness modulus which correlates well with field performance.

Gupta et al. (2023) explored the healing potential of reclaimed asphalt pavement (RAP) binders blended with different rejuvenators using the Linear Amplitude Sweep test, both with and without rest periods. It was observed that the inclusion of rest periods significantly enhanced the healing potential of the binders. A study by Yue et al., (2021) on Sasobit and polymer modifiers on asphalt binders the addition of WMA enhanced the self-healing ability of styrene–butadiene–styrene-modified asphalt and crumb rubber-modified asphalt. Also, asphalt binders showed significant improvement in their self-healing after the rest period. Pang et al. (2012) explored the self-healing capabilities of asphalt binders and determined that aging and SBS modification had a notable impact on healing. The study also observed that extended rest periods delayed the crack formation and subsequently increased the service life.

Although substantial progress has been made in assessing the fatigue performance of warm mix asphalt binders, their self-healing potential remains relatively underexplored. The present study aims to evaluate the healing potential of an unmodified binder blended with a WMA additive. For this purpose, the conventional LAS test has been modified to incorporate rest periods of varying durations. This approach will allow a quantification of the relative healing behavior of the binder with and without WMA additive.

2 EXPERIMENTAL INVESTIGATION

This study is carried out on a VG-40 binder (IS 73, 2013), and this base binder is blended with a chemical warm mix additive in order to prepare the warm mix binder. Prior to the addition of the WMA additive, the base binder was heated at 120°C in the oven for 30 minutes. Further, 0.1% of WMA additive by the weight of the binder was added and the mix was blended at a constant speed in a shear mixture at 120°C for 10 minutes. The binders, viz, VG-40 and VG-40+0.1% WMA additive, are further referred to as VG-40 and VG-40+WMA, respectively. Table 1 and Table 2 show the properties of the WMA additive and the bituminous binders respectively.

Table 1. Properties of the WMA additive

Properties of WMA additive	**Values**
Physical State	Liquid
Color	Pale Yellow
Odour	Slight Aromatic
Melting Point (°C)	-10
Boiling Point (°C)	200
Density (g/cm^3)	1.03
Water Solubility	Soluble

Table 2. Physical Properties of Binders

Tests	Binders	
	VG-40	VG-40 + WMA additive
Specific gravity	1.03	1.03
Softening point (°C)	53	52
Penetration grade at 25°C (0.1 mm)	51	49
Rotational viscosity (@135°C) (cP)	625	500

2.1 *Continuous LAS test*

The LAS test was conducted in accordance with AASHTO TP 101 (2014) wherein, the fatigue endurance of bituminous binders was estimated under the application of a continuous linearly ramping strain amplitude. In this investigation, the LAS tests were carried out using an Anton Paar MCR 302 dynamic shear rheometer (DSR) with an 8 mm parallel plate geometry and 2 mm gap setting at the intermediate temperature of 25°C.

The LAS test was performed on long-term aged binders. The oven-drying method was used for long-term aging, where a 650 μm thin layer of bitumen is placed on a plate and heated at 163°C for 4 hours to simulate short-term aging, and at 85°C for 3.5 days to simulate long-term aging (Behera et al., 2013). During the LAS test, the binder was subjected to oscillatory shear loading, and the strain amplitude increases linearly from 0 to 30% over 3,100 cycles at 10 Hz frequency. During the test, peak stress and strain are captured every 10 cycles, and the dynamic shear modulus and phase angle are calculated for all these cycles.

Before the LAS test, a frequency sweep was performed to obtain information on the undamaged material parameters, such as the complex shear modulus. A frequency sweep test was conducted by applying an oscillatory shear at 0.1% strain amplitude across a range of frequencies that range from 0.2 to 30 Hz at 25^{o}C.

2.2 *LAS test with rest periods*

The healing-based LAS test procedure comprises two distinct steps. Initially, a standard continuous LAS test is conducted without any interruption. The damage accumulation in the material is denoted as the damage level (D) and the damage intensity is defined as the normalized accumulated damage, represented by (S), with Sf indicating the critical threshold for failure. Further, rest periods are introduced at 25% and 75% of Sf, respectively, prior to reaching failure to examine their impact on the further evolution of damage. Varied rest periods (10 and 30 minutes) are tested at each damage level to analyze their effects on the binder response. Two replicates of all the above combinations were tested for ensuring repeatability.

2.3 *Data Analysis*

The viscoelastic continuum damage (VECD) concept is used to analyze the LAS test data *(*Bhasin et al., 2008; Karki et al., 2017*)*. As per AASHTO TP 101, the damage accumulation in the sample is determined using Equation 1,

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

where $C(t)$ is given by Equation 2.

$$C(t) = \frac{|G^*|(t)}{|G^*|(initial)} \quad (2)$$

Pseudo stiffness ($C(t)$) is calculated as the ratio of the dynamic shear modulus $|G^*|$ at time, t, and the "undamaged" initial modulus ($|G^*|$). γ_0 is the applied strain for each data point (% strain), and 'α' is obtained from the frequency sweep test. As seen from Equation (1), the total damage at 30% stain is the summation of the damage occurring in the material at each strain increment. The relationship between C(t) and D(t) is modeled using a power law function given by Equation 3.

$$C(t) = C_0 - a(D)^b \quad (3)$$

where C_0 takes the value 1, and a, b are constants. The value of *D(t)* at failure is denoted by D_f and is computed as Equation 4.

$$D_f = \left(\frac{C_0 - C_{peak\ stress}}{a}\right)^{1/b} \quad (4)$$

Figure 1 shows the plot of Damage intensity (S) vs Pseudo stiffness (C) is referred to as the damage characteristic curve (DCC) (Xie et al. 2017). The damage characteristic curves before the rest periods are the same, while those after the rest periods lie above the continuous damage characteristic curves. This indicates some recovery in stiffness due to the applied rest periods.

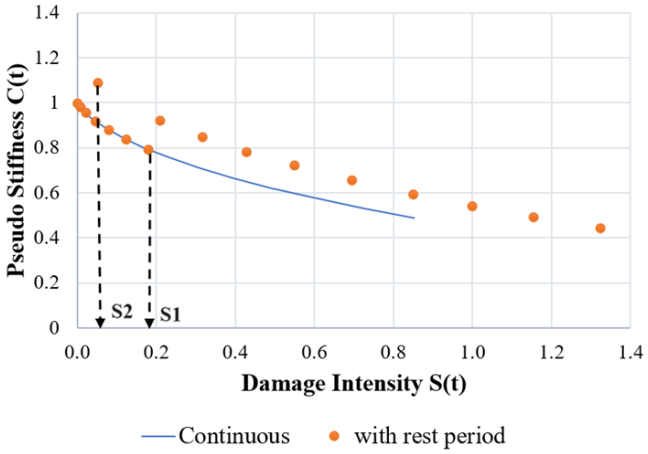

Figure 1. DCC curves with and without rest period

$$\%H = \left(\frac{S_1 - S_2}{S_1}\right) * 100 \quad (5)$$

The calculation of healing (%H), involves the damage (S) values before ($S1$) and after ($S2$) the rest period and is given in Equation 5.

3 RESULTS AND DISCUSSIONS

3.1 Continuous LAS test

Figure 2 shows the Damage Characteristic Curve (DCC) for the binders in a continuous LAS test

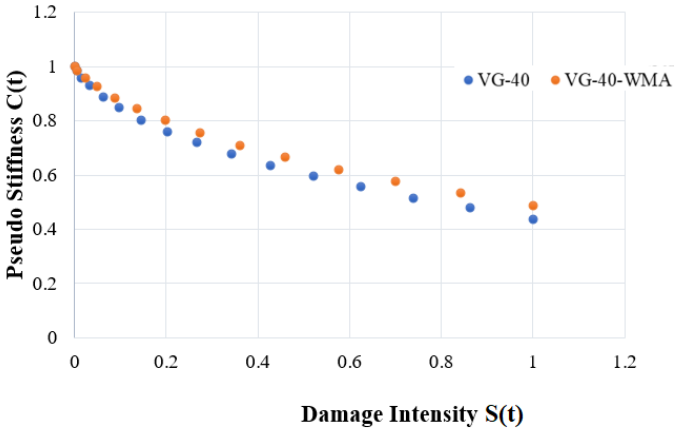

Figure 2. Damage Characteristic Curves for binders

It can be observed that the addition of a WMA additive to an unmodified binder has improved the stiffness of the binder at higher damage levels.

3.2 LAS test with rest periods

Figure 3 shows the results of the continuous LAS test and the LAS test with a rest period for both VG40 and VG40+WMA. Here, the rest period is applied at 25%Sf. It can be observed that when rest periods are applied at an early stage of damage (25%Sf), there is a complete recovery in the damage in both binders. Notably, the extent of stiffness recovery increases with the length of the rest periods.

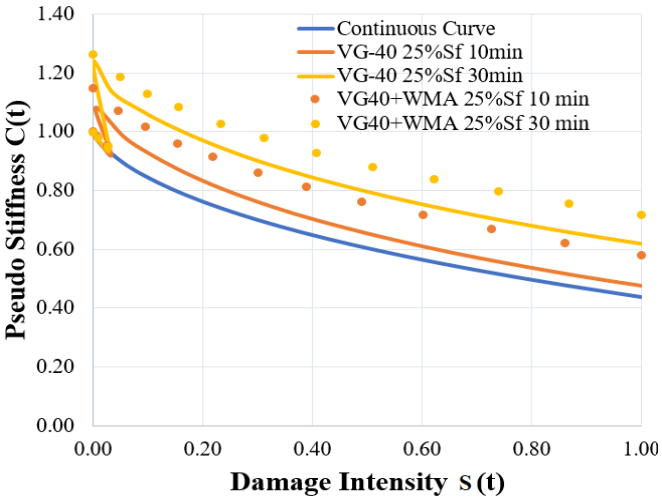

Figure 3. DCC at 25% Sf

It can be noted that the damage recovery has improved by adding a WMA additive to the VG40. The stiffness (C) in the WMA blended VG40 has also improved. At the same damage intensity, VG40 +WMA has better stiffness as compared to an unmodified binder.

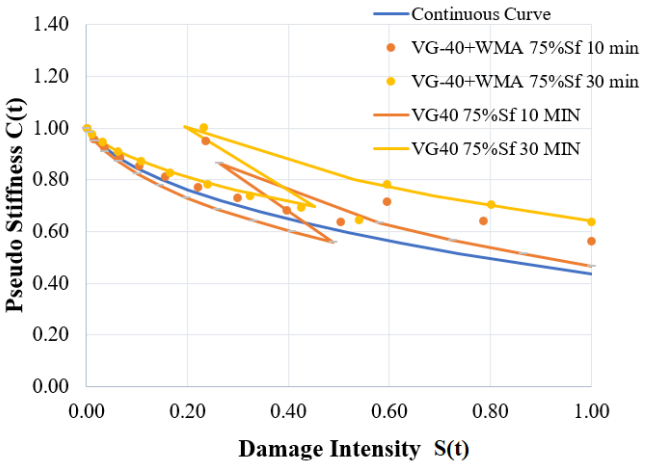

Figure 4. DCC at 75%Sf

It is observed from Figure 4 that the application of rest periods at higher damage levels (75%Sf) has a lesser impact on the healing of the binders. When rest period is given at 75%Sf, stiffness recovery is lower than that at 25%Sf. Also, the damage recovery is much lower. It can be noted that the rest period

duration is also less significant at higher damage levels. The addition of WMA has resulted in better stiffness and damage recovery even at 75%Sf. This underscores the potential of WMA additives to enhance the healing of binders in addition to their well-known benefits in reducing working temperatures.

3.3 Calculation of healing Index

The healing index (%) was evaluated for VG40 and VG40+WMA at two different damage levels (25%, and 75%Sf) and rest periods (10 and 30 minutes) as presented in Table 3.

Table 3. Healing Index

Healing Index (%)			
Binder	%Sf	Rest period (minutes)	
		10	30
VG40	25	85	100
	75	46	54
VG40+ WMA	25	100	100
	75	53	57

The results indicate that the healing percentage diminished with an increase in the damage levels, possibly due to excessive internal damage that cannot be reversed during the given rest periods. Also it can be observed that incorporating WMA additives into VG40 improved its healing performance across all damage levels.

4 CONCLUSIONS

- Application of rest periods during the LAS test results in binder healing and enhanced stiffness during the rest of the test.
- It is understood that the application of rest periods at higher levels of damage has a reduced effect on the healing of binders.
- The addition of the WMA additive has improved the healing index of VG40 at all the damage levels pre-failure.
- The results highlight the potential of WMA to enhance healing in binders, in addition to its established benefits in lowering working temperatures.

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