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A framework for the analysis of damage and recovery characteristics of asphalt mixtures

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ABSTRACT
This study presents two approaches for evaluating damage and recovery characteristics of asphalt mixtures. The first approach focuses on determining damage by extracting recoverable viscoelastic strain that has no damage and comparing it with the strain response of a material that has damage. The second approach is based on identifying the capacity of asphalt mixtures to recover some of the damage that may occur during creep loading. The advantage of these approaches is that they utilise experimental data to extract damage and recovery responses, without detailed mathematical modelling of material behaviour. The developed approaches are used to analyse the behaviours of fine aggregate mixtures (FAM) incorporating warm mix additives. The results show that these mixtures vary in their damage and recovery characteristics. For example, Sasobit FAM experienced the highest damage among mixtures, but it also had the highest recovery. Ageing was found to reduce the differences among mixtures in terms of resistance to damage, but it had less effect on the differences in their healing potential.

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Warm mix asphalt; fine aggregate mixtures; viscoelasticity; damage; recovery

Introduction

Damage and recovery of asphalt mixtures are complex phenomena that involve different deformation and cracking mechanisms, and are influenced by loading and environmental factors. Various experimental and modelling approaches have been proposed by researchers to characterise asphalt mixture damage and recovery characteristics.

Several experimental studies attempted to characterise damage by analysing changes in material response during repeated or dynamic loading. For example, Van Dijk and Visser (1977) proposed an approach to calculate the total energy dissipated due to crack initiation and propagation. Dissipated energy is represented by the area encircled by the stress–strain hysteresis loops. However, this method has the limitation of being dependent on the loading mode (stress controlled vs. strain controlled) and not differentiating among the various components of dissipated energy (viscoelastic, viscoplastic and damage). Ghuzlan and Carpenter (2000) built on this approach but proposed using the rate of change in dissipated energy between consecutive loading cycles in order to overcome the issue of dependence on the loading mode.

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In the modelling domain, Schapery (1984) introduced the concept of pseudo-strain (or pseudo-stress) as a mean to separate the energy dissipated because of the viscoelastic response from the energy dissipated due to damage. Consequently, the viscoelastic continuum damage (VECD) approach was developed to evaluate the fatigue resistance of asphalt mixtures by postulating an internal damage 'S' function, which is not affected by sample geometry, loading rate, or mode (Lee et al., 2003; Schapery, 1987). The VECD approach was further developed and implemented to characterise damage in asphalt mixtures subjected to various loading and environmental conditions (Kutay et al., 2008; Lancaster & Khalid, 2015; Sadek, 2015; Sadeq et al., 2016; Underwood, 2011). A simplified VECD approach was also presented by Underwood et al. (2012) in order to facilitate its implementation in performance analysis. Masad et al. (2008) presented a method that separated the dissipated pseudo-strain energy into three components associated with a change in phase angle between load cycles, a change in phase angle within a single cycle, and a change in stiffness between cycles. Masad et al. (2008) showed that this separation approach allows for comparison of mixtures irrespective of the mode of loading (stress-controlled vs. strain-controlled tests). A comprehensive computational modelling framework was developed in recent years to simulate the behaviour of asphalt pavements based on modelling its viscoelastic, viscoplastic, damage, and healing components (Abu Al-Rub et al., 2012; Darabi et al., 2011, 2012, 2013; Huang et al., 2011).

Kim et al. (1990) studied damage recovery or healing in asphalt mixtures by monitoring changes in pseudostrain energy during rest periods inserted at different stages in the fatigue test. Following this analysis approach, Si et al. (2002a, 2002b) monitored changes in pseudostiffness during loading and rest periods, and they concluded that the increase in pseudostiffness during rest periods is a good measure of healing. Kim et al. (2003) introduced rest periods at different stages of dynamic loading and proposed that the increase in dynamic modulus during rest periods is a measure of healing potential. Shenoy (2008) proposed to use the storage and loss viscoelastic moduli obtained from an oscillation tests to quantify mixture recovery. Luo (2012) discussed this method and argued that the oscillation test is conducted at a high frequency that does not allow for a full recovery to be transferred from the loss modulus to the storage modulus. Hence, Luo (2012), Luo et al. (2013) presented a new method to measure recovery by capturing the so called 'internal stresses' that develop during rest periods between loading cycles. In a follow-up study, Luo et al. (2015) quantified damage density and reported that it decreased during the recovery period, which is an indication of healing.

This paper proposes analytical approaches for characterising damage and recovery of asphalt materials based on the analysis of creep-recovery testing results. These approaches rely on quantifying parameters that separate damage from the material's viscoelastic and viscoplastic responses. The efficacy of this approach is demonstrated through the analysis of various fine aggregate mixtures (FAM) prepared using a control asphalt and warm mix asphalt (WMA) additives.

Materials and experimental preparation

Fine aggregate mixtures (FAM) were prepared by mixing a polymer modified binder of PG 76-22 grade with Gabbro aggregates that pass sieve no. 4 (4.75 mm). The aggregate size distribution was determined to represent the fine portion of a typical mix that meets Qatar Construction Specifications (QCS). Then, 150 mm diameter specimens were compacted using the Superpave Gyratory Compactor (SGC) to a specific height in order to control percentage air voids. Cylindrical FAM samples were cored and cut from the SGC specimens to a height of 50 and 12 mm in diameter. The average per cent air voids of the FAM specimens (cored and cut to a height of 50 and 12 mm in diameter) was about 3.0%. A total of four FAM mixtures were included in this study. The first one is the control, i.e. Original mixture that had no WMA additive, while the other three had warm mix additives: Sasobit, Advera, and Rediset at 2%, 5%, and 0.5% dosage level of binder weight, respectively. Previous studies have shown that FAM specimens exhibit more uniform air voids distribution and yield less variability in fatigue tests than full specimens of asphalt mixtures (Howson et al., 2007; Sadeq et al., 2016; Suresha & Ningappa, 2018).

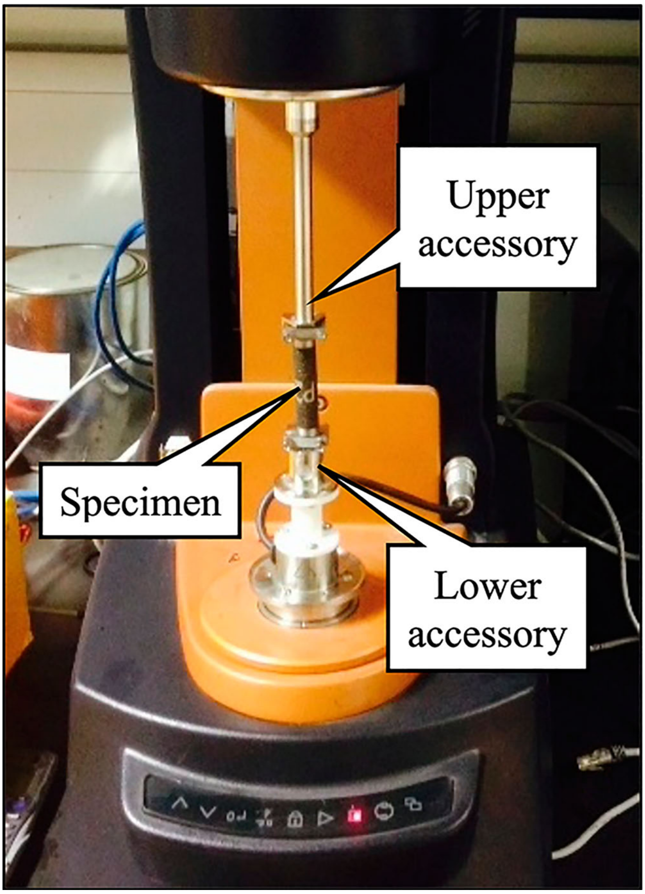


Figure 1. DSR with the attached accessory and solid FAM specimen.

In order to investigate the ageing effect on damage and recovery characteristics, FAM test specimens were subjected to an ageing protocol using an accelerated weathering machine for 2455 h using cycles of UV light at an intensity of 0.89 W/m^2 and a temperature of 50°C. The ageing protocol presented one year of outside exposure (Sadeq et al., 2017).

The creep/recovery test was conducted using a Dynamic Shear Rheometer (DSR). Metal-end pieces were glued to FAM specimens which were then attached to concentrically aligned steel shafts that enable the DSR machine to apply a torsional force on the specimen. Figure 1 shows the DSR with an attached specimen ready for testing. Three replicates were tested for each combination of mixtures and ageing level at a controlled room temperature of 25°C. The total test of specimens was 24 (four mixtures, three replicates without ageing, three replicates with ageing).

Repeated creep and recovery test protocol

In order to characterise the linear viscoelastic (LVE) properties of the various mixtures, a one-cycle creep and recovery test was conducted for each mixture at both ageing levels (unaged and aged conditions). The applied loading stress level was selected to be 75 kPa in order for the material response to remain in the LVE region based on stress sweep tests in previous studies (Sadeq, 2017; Sadeq et al., 2016). The test was designed to apply a creep (step-loading) for 40 s followed by 85 s of recovery time based on an earlier work by Luo (2012). This long recovery time was used to ensure that the material recovers its viscoelastic strain. Following this small-stress test, the specimen remained in the test setup

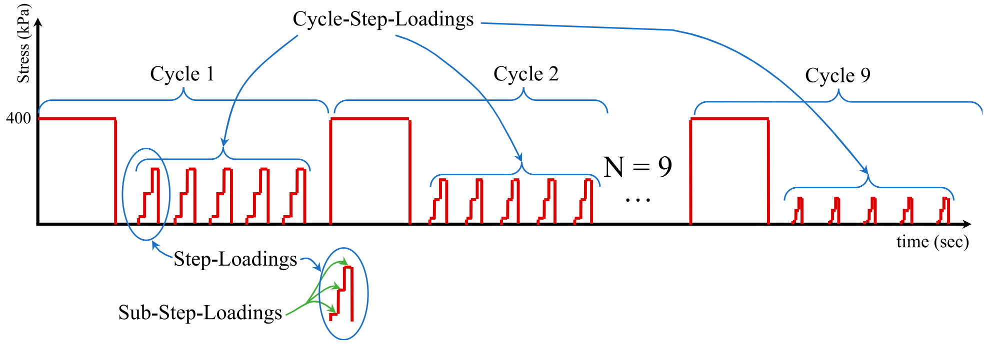


Figure 2. Repeated creep and recovery test protocol with the inclusion of cycle-step-loadings in the recovery phase.

for at least 10 min and then it was subjected to nine cycle-loadings at a stress level of 400 kPa for 40 s duration and a recovery time according to Equation (1).

$$T_i(\text{sec}) = 85e^{0.1579(i-1)} \tag{1}$$

where 'T_i' is the recovery time of cycle-loading 'i' (i.e. 1–9). Equation (1) was formulated after conducting multiple trial tests in order to achieve recovery of viscoelastic strain following each loading cycle.

During the recovery time, five cycle-step-loadings were applied and the response was used to determine the amount of 'internal stresses' following the concept presented originally in the strain transient dip test (Ahlquist & Nix, 1971; Luo et al., 2013; Teoh et al., 1987). Each step-loading consisted of three sub-step-loadings, as shown in Figure 2. The stress levels of sub-step-loading within the recovery period of the first cycle were selected as 1%, 20%, and 50% of the 400 kPa cycle-loading stress level. By moving to the next cycle, the stress level of sub-step-loading was reduced by 10% of the previous cycle-step-loading stress level, and so on. The durations of all sub-step-loadings were set to be 2 s. A diagram of repeated creep and recovery test is shown in Figure 2.

Damage analysis approach

Viscoelastic properties from the small stress creep and recovery test

The first step of this analysis approach is to obtain the viscoelastic properties from the measurements of the one-cycle creep and recovery test at low-stress level (75 kPa). The viscoelastic relation in Equation (2) is used to represent the recoverable strain ($\varepsilon(t)$) of the FAM specimen (Schapery, 1969).

$$\varepsilon(t) = D_0\sigma + \int_0^t \Delta D(\Psi - \Psi^t)\frac{d\sigma}{d\tau}d\tau \tag{2}$$

where D_0 is the instantaneous compliance, $\Delta D(\Psi - \Psi^t)$ represents the transient compliance, σ is stress and τ is time. In this study, we did not consider the instantaneous response because it was not possible to separate the elastic response from the time-dependent response at the test temperature. Consequently, all the strain response was considered to be time-dependent. For a step loading, the recoverable strain during creep and recovery can be derived from Equation (2) as shown in Equations (3) and (4), respectively.

$$\varepsilon^c(t) = \sigma D(t) \tag{3}$$

$$\varepsilon^r(t) = [\sigma D(t) - \sigma D(t - t_a)] \tag{4}$$

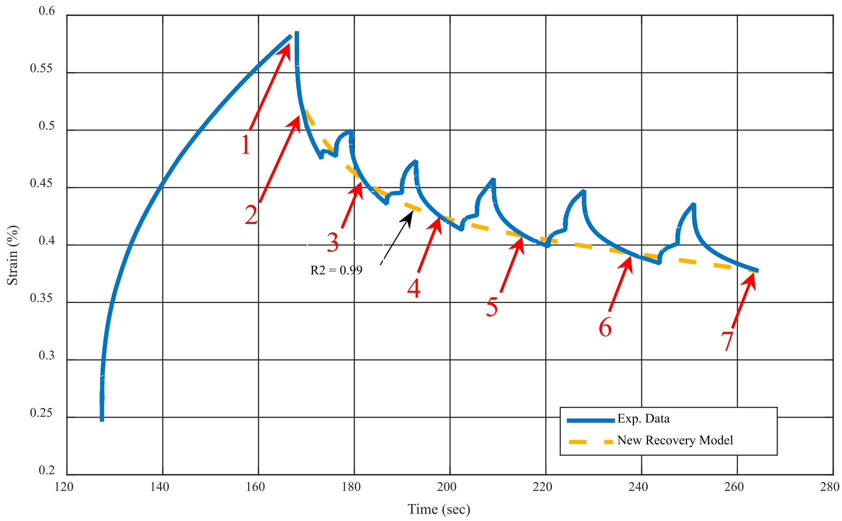


Figure 3. Example of fitted recovery strain with the model using seven specific points in the experimental data.

where t_a is the time at the end of loading phase and $D(t)$ can be represented by Prony series model as shown in Equation (5).

$$D(t) = \sum_{n=1}^{N} D_n(1 - e^{-t\lambda_n}) \tag{5}$$

where D_n is n^{th} coefficient of Prony series associated with n^{th} retardation time λ_n.

This research employs a separation analysis procedure to decouple the recoverable strain (VE strain) from the total strain. Since the irrecoverable strain does not evolve during the recovery period, the recovered strain $\Delta\varepsilon(t)$ can be obtained by subtracting the recovery strain $\varepsilon^r(t)$ from the creep strain $\varepsilon^c(t_a)$ at $t = t_a$. Consequently, the Prony series coefficients can be obtained by fitting the measurements of recovered strain $\Delta\varepsilon(t)$ using Equations (3) and (4). More details about the decoupling process can be found in a study by Masad et al. (2009). The obtained Prony series coefficients were then utilised to represent the viscoelastic (VE) response with no damage in the following analysis.

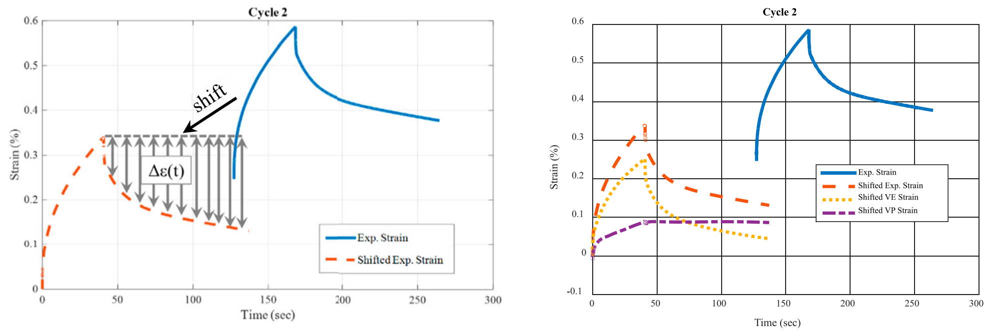
Recoverable response without damage

In order to obtain the response without the effects of the step-loadings, we used an approach to smooth the recovery phase measurements of the repeated creep and recovery test (Karki et al., 2014). Seven points were selected from the original recovery strain and a second-degree exponential model ($\varepsilon_r(t) = ae^{-bt} + ce^{-dt}$) was used to reproduce the recovery strain without losing the trend of the response as shown in Figure 3.

The Prony series coefficients obtained from the small-stress creep and recovery test were employed to calculate the recoverable (VE) strain for all cycles of the repeated creep and recovery test conducted at high stress level (400 kPa). The calculated VE strain represents the recoverable response without viscoplastic deformation and/or damage. This strain response referred to in this study as 'VE Strain (ε^{VE})' to reflect the absence of damage and viscoplasticity.

Recoverable response with damage

In order to capture the recoverable response that includes damage but no viscoplastic deformation, the following process was used to analyse the creep and recovery cycles:



(a) (b)

Figure 4. An example of (a) Recoverable strain extracted from the second cycle after shifting (b) Obtaining the VE and VP strains of shifted cycle 2 of the repeated creep and recovery test.

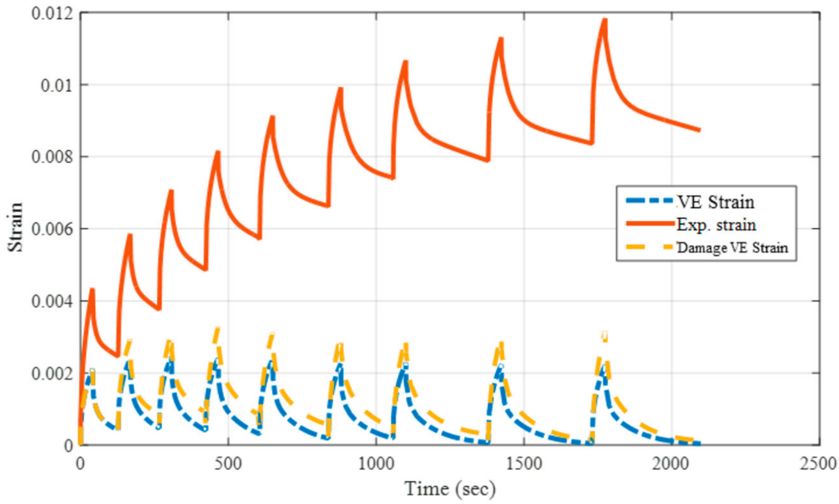


Figure 5. Example of VE strain and Damage VE strain for all cycles for the repeated creep and recovery test.

(a) Each cycle was shifted from its first data point to the origin (zero strain and zero time) as shown in Figure 4(a). The shifting did not affect the trend of recoverable response because the vertical shifting kept the same evolution of strain and the horizontal shifting retained the same duration of creep and recovery.
(b) The recoverable strain $\Delta\varepsilon(t)$ was determined from the recovery phase, as shown in Figure 4(a), and $\Delta\varepsilon(t)$ was used to obtain a new set of Prony series coefficients using the same analysis procedure presented earlier for one-cycle creep and recovery test.
(c) The Prony series coefficients were utilised to calculate the recoverable strain with damage.
(d) The unrecoverable viscoplastic strain was obtained by subtracting the results from step 'c' above from total strain. The decouple results are shown in Figure 4(b).

The shifted VE strain shown in Figure 4(b) represents the viscoelastic (VE) strain with damage excluding the viscoplastic (VP) strain. The strain is referred to as 'Damage VE Strain (ε_D^{VE})'. Then, ε_D^{VE} was relocated back to its original location and attached to the first data point of the VE strain (ε^{VE}) of the cycle. The process was repeated for all cycles and an example of the results is shown in Figure 5 for both ε^{VE} and ε_D^{VE}.

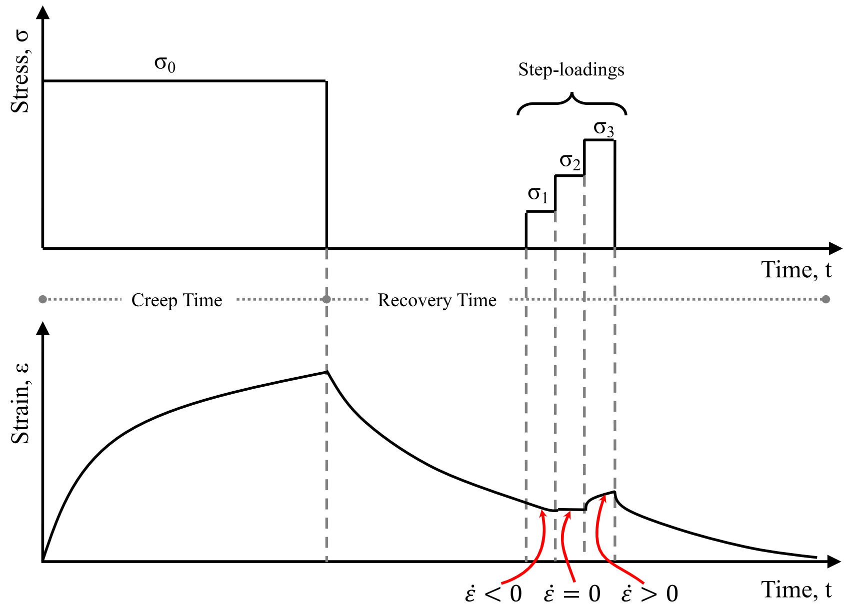


Figure 6. Schematic of strain transient dip test (Luo, 2012).

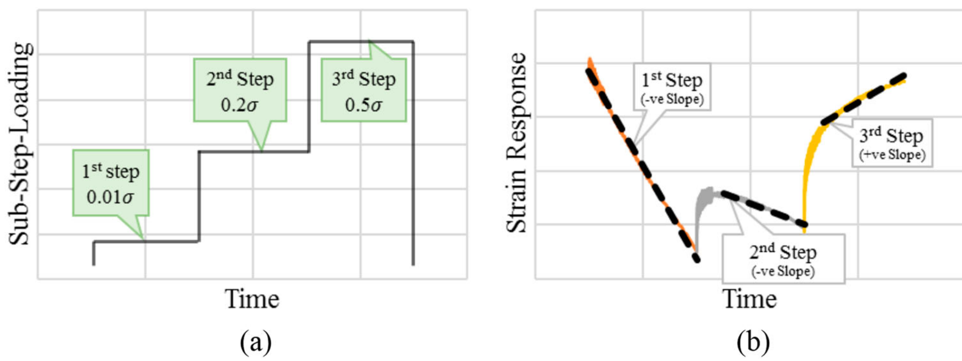


Figure 7. Example of (a) applied sub-steps-loading within a step-loading and (b) fitting the strain measurements.

Recovery analysis approach

Internal stress is a residual stress that drives the material to relax during a rest period (Luo et al., 2013). Ahlquist and Nix (1971) conducted a study that characterised the internal stress using the strain transient dip test, which involves applying a step-loading that includes several sub-step-loadings as shown in Figure 6. The stress that achieves a strain rate ($\dot{\varepsilon}$) of zero indicates the balance between the applied sub-step-loading and the internal stress of the material. The internal stress concept is employed in this study to evaluate the capacity of the asphalt material for strain recovery.

The use of sub-step-loadings in the recovery phase resulted in measuring the strain values for each sub-step-loading. These strain values were fitted using a linear function. Figure 7 shows the sub-step-loading for one step-loading and the resultant strain fitted with linear trend.

The negative strain rate (slope) indicates that the applied stress level of sub-step-loading is less than the internal stress needed to reverse the material's recovery response. However, a positive strain rate indicates that the applied stress level of a sub-step-loading is high enough to reverse the material's response and to accumulate more creep strain. The obtained strain rates of each sub-step-loading are

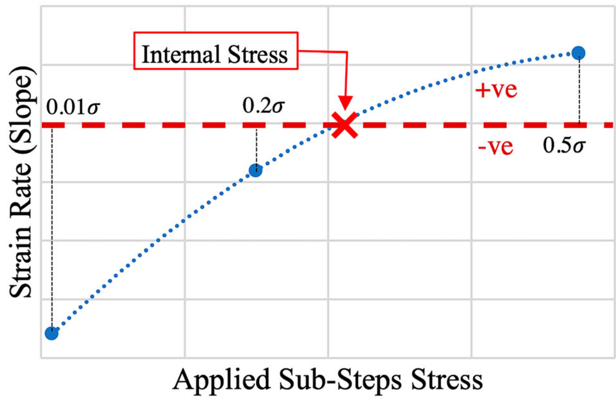


Figure 8. Fitting resultant strain rate.

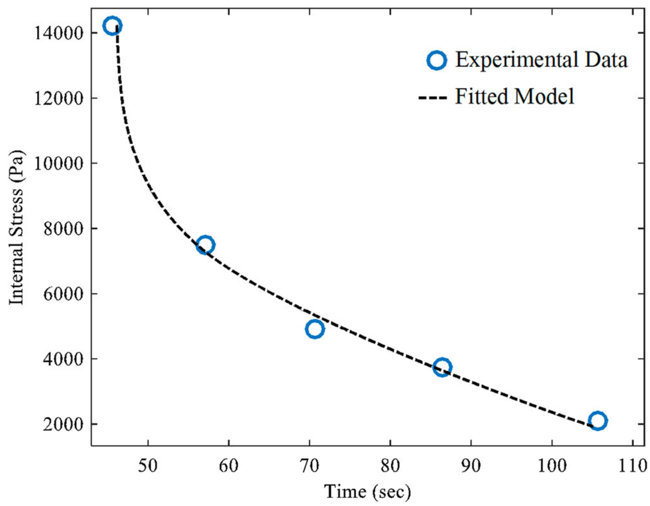


Figure 9. An example of internal stress values for a cycle-loading.

plotted against the corresponding applied stress levels as shown in Figure 8. A polynomial function is used to regress the relationship between strain rate and applied stress levels and the interception of the polynomial curve with the stress axis is identified as the internal stress that generates a zero-strain rate. This analysis process is repeated for each step-loading in each cycle to identify the internal stress.

Within each recovery phase, five internal stresses (from five step-loading) can be obtained as shown in Figure 9. The figure shows that internal stresses decrease during the recovery phase, which is attributed to relaxation behaviour of viscoelastic material. In other words, the material recovery capability decreases with time during the rest period. In order to normalise the internal stress results for a proper comparison, it was fitted by a second-degree exponential function ($\sigma_i(t) = ae^{bt} + ce^{dt}$) and divided by the strain's second-degree exponential function ($\varepsilon_r(t) = ae^{-bt} + ce^{-dt}$) to calculate the Recovery Modulus (R_M). The recovery modulus represents the ability of material to recover strain that accumulates during loading (Luo et al., 2013). Figure 10 illustrates the experimental and analysis approaches followed in this study.

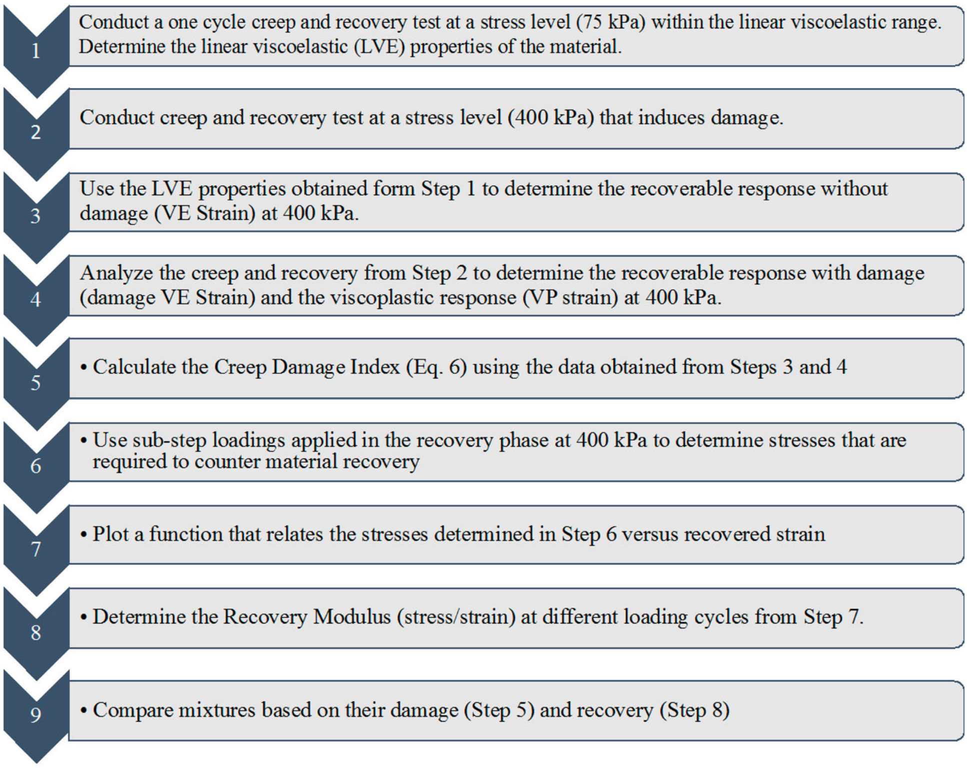


Figure 10. Description of the approach for the analysis of damage and recovery.

Table 1. Percent of increase between unaged and aged specimens for all mixtures at the ninth cycle.

	Recovery modulus, MPa at 9th cycle	
Mix type	Unaged	Aged
Original mix	0.13	0.27
Sasobit mix	0.25	0.32
Advera mix	0.19	0.27
Rediset mix	0.08	0.14

Analysis and results

The results are presented for all mixtures (Control/Original, Sasobit, Advera and Rediset) in aged and unaged conditions. The results of two analysis approaches: recovery analysis approach and damage analysis approach are discussed in the following sections.

Recovery analysis approach results

The recovery modulus of each mixture with unaged and aged condition is presented in Figure 11. In addition, Table 1 summarises the results of recovery modulus at the ninth cycle for all mixtures. The recovery modulus decreases with more loading cycles indicating the reduction of recovery capability. The Sasobit mixture had the highest recovery modulus, while the Rediset mixture exhibited the lowest recovery modulus compared to the other mixtures in both unaged and aged conditions. It is interesting to note that the results in Figure 11 and Table 1 show that ageing increased the recovery modulus of all mixtures (i.e. increased the recovery capability). Ageing stiffened the FAM specimens,

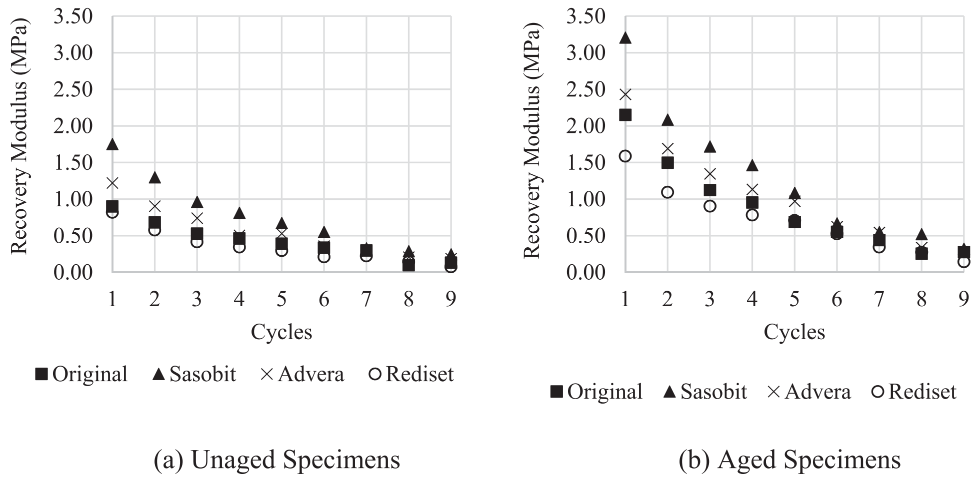


Figure 11. Recovery modulus for all mixtures at unaged and aged status.

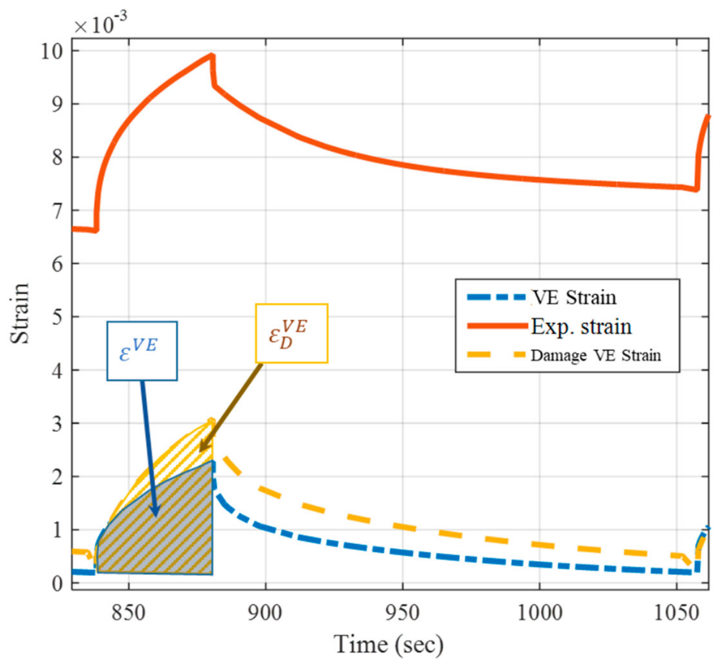


Figure 12. Area used to calculate the difference between undamaged and damaged VE strain in the creep phase.

which increased internal stresses that help the material to recover during rest periods or unloading. However, as shown in the following section, performance should be assessed using a framework that accounts for both damage resistance and recovery and not only by one of them.

Damage analysis approach results

As discussed earlier, ε^{VE} donates the recoverable strain without damage, while ε_D^{VE} indicates the recoverable strain with damage. The area under (ε_D^{VE} and ε^{VE}) shown in Figure 12 is used to calculate the creep damage index (δ_C) as shown in Equation (6), which represents the percentage of damage

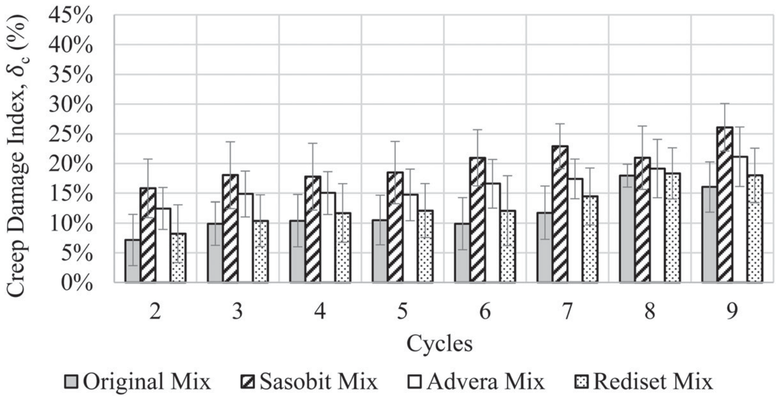


Figure 13. Damage evolved during creep phase for unaged Original, Sasobit, Advera and Rediset mixtures tested with the repeated creep and recovery test (error bars represent standard error).

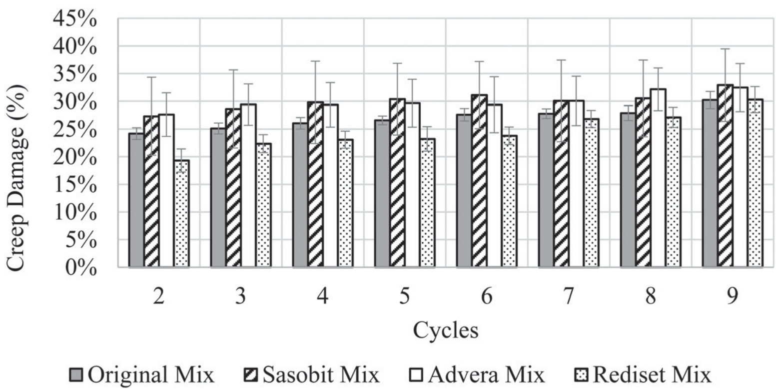


Figure 14. Creep damage for aged Original, Sasobit, Advera and Rediset mixtures tested in repeated creep and recovery test (error bars represent standard error).

evolving within creep phase:

$$\delta_C(\%) = \frac{\text{Area Under}(\varepsilon_D^{VE}) - \text{Area Under}(\varepsilon^{VE})}{\text{Area Under}(\varepsilon_D^{VE})} \times 100\% \quad (6)$$

The results of the creep damage (δ_C) for unaged mixtures are shown in Figure 13, while the results of the aged specimens are shown in Figure 14. The error bars in both figures are standard errors which are calculated by dividing the standard deviation by the square root of the sample size (three replicates). Creep damage increased with an increase in number of cycles. Table 2 summarises the results of creep damage index at the ninth cycle for unaged and aged specimens. The highest creep damage was in the Sasobit mixture followed by Advera, Rediset, and Control mixtures.

The results of the Recovery Modulus and Creep Damage Index at the ninth cycle are presented in Figure 15. As discussed earlier, ageing improved recovery, but at the same time, it increased damage for all mixtures. In addition, it can be noticed that ageing reduced the difference among mixtures in terms of resistance to damage, while it had much less effect on the differences in their recovery potential. Among the warm mixtures, Sasobit had the highest creep damage, but at the same time had the highest recovery modulus. Rediset mixture, on the other hand, had the lowest recovery modulus, while its creep damage was similar to other mixtures. This framework that combines damage and recovery

Table 2. Results of creep damage index at the ninth cycle for both unaged and aged mixtures.

	Creep damage (δ_C), % at 9th cycle	
Mix type	Unaged	Aged
Original mix	16	30
Sasobit mix	26	32
Advera mix	21	32
Rediset mix	18	30

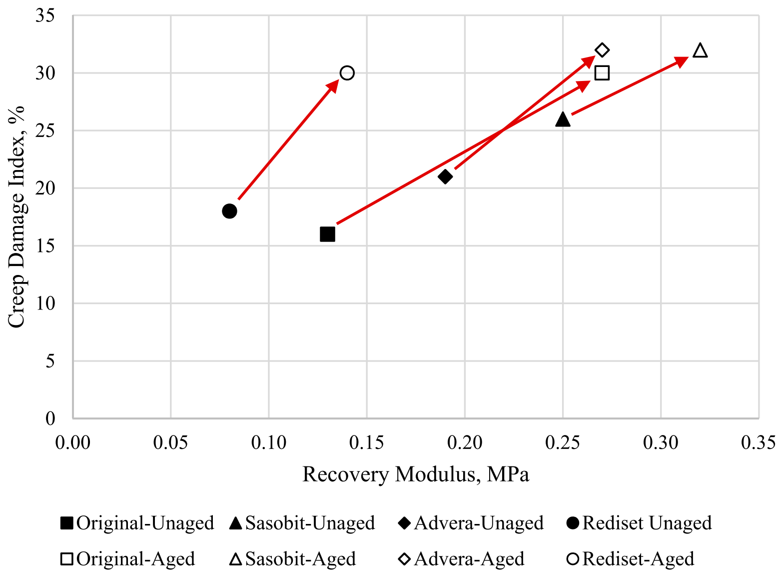


Figure 15. The change in creep damage index and recovery modulus with ageing for WMA mixtures at the ninth cycle.

characteristics can be used to differentiate between good performing mixtures (low damage, high recovery) and poor performing mixtures (high damage, low recovery).

Summary and conclusions

This study presented a testing protocol and analysis approaches to evaluate the damage and recovery characteristics of asphalt mixtures. The first approach quantifies the amount of damage by comparing the undamaged viscoelastic strain with damaged viscoelastic strain. The second approach calculates the recovery modulus, which is equal to the internal stresses divided by the recovered strain. A higher modulus value indicates better recovery capability. Both approaches rely on analysis of experimental data to separate the viscoelastic, viscoplastic, damage, and recovery components without the need for detailed mathematical modelling. This facilitates the implementation of the developed approaches in simple spreadsheets or programmes.

The damage and recovery approaches were used to evaluate asphalt mixtures prepared with and without warm mix additives, and the main conclusions are as follows:

(1) The developed framework combines both damage and recovery characteristics. Therefore, it can be used to identify good performing mixtures (low damage, high recovery) and poor performing mixtures (high damage, low recovery).
(2) The Sasobit mixture had the highest creep damage, but at the same time had the highest recovery modulus. The Rediset mixture, on the other hand, had the lowest recovery modulus.

(3) Ageing improved recovery, but at the same time, it increased the damage for all mixtures.
(4) Ageing reduced the differences among mixtures in terms of resistance to damage, while it had much less effect on the differences in their recovery potential.

It is recommended to use the analysis approach to evaluate full asphalt mixtures as well as fine aggregate mixtures (FAM) that incorporate different materials. The results can then be compared to other conventional damage tests and field performance.

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