Fatigue resistance investigation of warm-mix recycled asphalt binder, mastic, and fine aggregate matrix

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Abstract
Fatigue cracking is one of the primary distresses in warm-mix recycled asphalt pavements. This paper evaluates the fatigue resistance evolution of warm-mix recycled asphalt materials in different scales during the service period. The strain sweep test and time sweep test were performed, respectively, by dynamic shear rheometer to determine the linear viscoelastic limits and to characterize the fatigue behavior of warm-mix recycled asphalt binder, mastic, and fine aggregate matrix with different ageing levels and recycling plans. The dissipated energy method was used to define the failure criterion and to construct the fatigue model. Effects of ageing levels and recycling plans on stiffness and fatigue resistance were investigated. Performance correlations among warm-mix recycled asphalt binder, mastic, and fine aggregate matrix were developed, respectively, by the statistical method to determine the critical material scale for stiffness and fatigue resistance.

KEYWORDS
asphalt ageing, dissipated energy, dynamic shear rheometer, fatigue resistance, multiscale, warm-mix recycling

1 | INTRODUCTION

One of the most important factors limiting the application of the hot recycling technique for asphalt pavements is the heating temperature. The reclaimed asphalt pavement (RAP) is not easy to be sufficiently heated because of device limitations, causing a low RAP utilization ratio or a poor pavement performance. The “green” warm recycling technique combining both warm mix asphalt (WMA) and recycling techniques may well compensate for this deficiency. Adding appropriate warm mix agent during the hot recycling process can effectively reduce mix, paving, and compaction temperatures over 30°C. One advantage is to increase the utilization ratio and to delay the ageing processes for RAP. In the United States and Europe, the field research shows that the RAP content used in recycled asphalt mixtures can reach 45% to 50% with the aid of the WMA technique.1,2 If the RAP content increases from 30% to 50%, it will save more than one fifth of the cost. It also has the advantage of saving

Nomenclature: $P_1,$ = pavement service period before recycling, year; $T_{1'},$ = PAV ageing time for the new binder, h; $P_2,$ = pavement service period after recycling, year; $T_{2'},$ = PAV ageing time for the warm-mix recycled binder, h; $N_f,$ = fatigue life; $DE,$ = initial dissipated energy density at the 50th loading cycle, kPa; $|G'|,$ = complex shear modulus, MPa; $a, b, c, d, e, f,$ = model coefficients; $r,$ = correlation coefficient; $x, y,$ = data sets; $cov(x,y),,$ = covariance of $x$ and $y; D(x), = variance of x; D(y), = variance of y$
energy and reducing construction pollution. Therefore, the warm recycling technique has been increasingly used in the asphalt pavement maintenance of high-grade highways in China.

Fatigue cracking is one of the major distresses affecting the asphalt pavement performance due to the short-term and long-term ageing of asphalt binder from RAP.\(^3\) The improvement by adding a certain proportion of new asphalt binder is not significant for recycled asphalt mixtures. The fatigue cracking problem of warm-mix recycled asphalt mixtures may be more severe because of the higher RAP content. Moreover, the coupling effect of the warm mix agent, rejuvenator agent, RAP, and new asphalt mixtures is complex in warm-mix recycled asphalt mixtures. The secondary ageing phenomenon of asphalt binder always accompanied during the service period will accelerate the pavement performance deterioration, especially the fatigue resistance. Therefore, there is an urgent need of studying the fatigue cracking resistance of warm-mix recycled asphalt mixtures during the whole service period.

A great deal of studies have been done to evaluate the fatigue resistance of various types of warm recycling techniques in recent years. Oliveira et al\(^4\) proposed that the asphalt mixture with 50% RAP and the surfactant-based WMA agent showed similar or slightly better fatigue performance than that without the WMA agent. Safaei et al\(^5\) found that differences between the fatigue performance of WMA and hot mix asphalt (HMA) were insignificant after the long-term ageing. Zhao et al\(^6\) reported that WMA mixtures with a high RAP content had better fatigue resistance than HMA mixtures with a high or a low RAP content regardless of WMA techniques and pavement layers used. Lopes et al\(^7\) observed that the warm-mix recycled asphalt mixture was more sensitive to fatigue than hot and warm mix mixtures without RAP. Different researchers obtained contradictory conclusions, indicating the lack of an in-depth understanding of the warm recycling technique.

Asphalt concrete can be considered in terms of at least 4 characteristic elements: binder, mastic, fine aggregate matrix (FAM), and mixture. Binder is the smallest scale and mixture is the largest, with mastic and FAM falling in between.\(^8\) Because fatigue damage occurs largely between coarse aggregate particles, laboratory tests on material scales of binder, mastic, and FAM can provide direct indications of how they will affect the mixture.\(^9\) In the scale of binder, test methods based on the dynamic shear rheometer (DSR) have always been the research focus, such as the frequency/temperature sweep test, the time sweep test, the stress/strain sweep test, the multiple stress creep recovery (MSCR) test, and the linear amplitude sweep (LAS) test.\(^10\) Besides, the elastic recovery test conducted using the ductility device and the double edge notch tension (DENT) test were also used for the additional evaluation of the binder fatigue resistance.\(^10,11\) In the scale of mastic, the DSR time sweep test and the direct tension fatigue test were selected to evaluate the effect of loading modes, stress levels, loading frequencies, temperatures, ageing levels, and additive types on fatigue performance.\(^12,13\) In the scale of FAM, Underwood and Kim\(^14\) performed the DSR temperature and frequency sweep test to evaluate the effect of volumetric properties (air void and binder content) on fatigue resistance. Mo et al\(^15\) developed a FAM fatigue model based on the dissipated energy concept for the porous asphalt pavements using the modified DSR shear fatigue test.

All tests based on each single material scale have some shortcomings, so the multiscale experimental tool has been selected to investigate the correlation of fatigue test results from different material scales.\(^8\) An empirical correlation was established by Underwood and Kim\(^14\) to link the failure strains of FAM and asphalt mixtures obtained from the direct tension test. Pérez-Jiménez et al\(^16\) applied a cyclic uniaxial tension-compression test to evaluate the fatigue properties of asphalt binder, mastic, and FAM. It showed that there was a good correlation among their fatigue strains. Mannan et al\(^17\) observed that fatigue lives of extracted binders from time sweep and LAS tests had a good correlation with those of recycled mixtures from the beam test. A strong correlation existing between the viscoelastic parameter of binder integrity and the fatigue resistance of asphalt mixtures was found by Ameri et al\(^18\) All these studies confirm the potential feasibility of the multiscale experimental method to evaluate the fatigue resistance for warm-mix recycled asphalt pavements.

The main objective of this study is to evaluate the fatigue resistance evolution of warm-mix recycled asphalt pavements with a high RAP content during the service period. To accomplish it, the DSR strain sweep test was conducted on warm-mix recycled asphalt binder, mastic, and FAM with different ageing levels to determine the linear viscoelastic (LVE) limits and strain levels used in fatigue tests. The DSR time sweep test was performed at 3 strain levels to characterize the fatigue behavior of warm-mix recycled asphalt materials in different scales. Effects of ageing levels and recycling plans were analyzed based on the dissipated energy method. Correlations of stiffness and fatigue properties among warm-mix recycled asphalt binder, mastic, and FAM were finally investigated.

2 | EXPERIMENTAL PLAN

2.1 | Binder ageing procedure

The laboratory simulation method was used to obtain the aged asphalt binder corresponding to different service
periods due to the lack of sufficient field core samples. The aged binder was further used to make mastic and FAM specimens. The binder ageing process was divided into 2 stages. In the initial stage, the virgin binder was aged to the expected degree to simulate the pavement ready for recycling. Then, the warm mix agent, rejuvenator agent, and new binder were added to complete the recycling process. In the secondary stage, the recycled binder was aged again to different levels to simulate warm-mix recycled asphalt pavements corresponding to different service periods. The binder ageing procedure is briefly introduced as follows. More details can be found elsewhere.\textsuperscript{19}

1. The virgin binder is aged 85 minutes at the temperature of 163°C using the rolling thin film oven test (RTFOT) to simulate the short-term ageing which occurs during the production and construction of new asphalt mixtures.
2. The residue after RTFOT is aged at the air pressure of 2.1 MPa and the temperature of 100°C using the pressure ageing vessel (PAV) to simulate the long-term ageing which occurs during the service period of new asphalt mixtures. For a given pavement service period, the PAV ageing time of the styrene butadiene styrene (SBS) modified binder is determined by the following equation.

\[
P_1 = 0.52T_1^{0.73}
\]

In which \(P_1\) is the pavement service period before recycling (year), and \(T_1\) is the PAV ageing time for the new binder (h).

3. According to the recycling plan, a certain amount of the warm mix agent, rejuvenator agent, and new binder are added into the aged binder after PAV.
4. The warm-mix recycled binder is aged once again at the same conditions as the virgin binder using RTFOT and PAV to simulate the secondary ageing behavior. The following equation is provided to determine the PAV ageing time for the warm-mix recycled binder.

\[
P_2 = 0.27T_2^{0.72}
\]

In which \(P_2\) is the pavement service period after recycling (year), and \(T_2\) is the PAV ageing time for the warm-mix recycled binder (h).

2.2 | Materials and specimen fabrication

The in-place recycling maintenance project of the Lianxu Highway located in Jiangsu of China was selected for study. During 2013, a total of more than 40 km (single lane) pavement sections were repaired by the warm recycling technique. The high RAP content recycled mixture was composed of 15% new mixture and 85% RAP. A low-viscosity liquid chemical WMA agent Evotherm 3G (5% of the total weight of the new and RAP binders) containing a surfactant and an antistrip additive was used to reduce the surface tension of the asphalt films and to protect against moisture damage. The rejuvenator agent (4% of the RAP binder weight) was added to help soften and recover the property of the RAP binder by reducing its viscosity and stiffness, and increasing its ductility. The styrene-butadiene rubber (SBR) latex (4% of the RAP binder weight) was used to improve the RAP binder performance.\textsuperscript{20} Three different recycling plans designed for this project are shown as follows:

- **Plan 1. WMA agent + Rejuvenator agent + SBR latex**
- **Plan 2. Rejuvenator agent + SBR latex**
- **Plan 3. WMA agent + Rejuvenator agent**

The SBS modified asphalt binder with the similar properties as that used in the field during the construction period was selected for the laboratory ageing simulation following the aforementioned procedure. The initial PAV ageing time for the virgin binder was 74 hours corresponding to approximate 12 years’ service of the highway before recycling maintenance. The secondary PAV ageing time of 0, 6, 16, 28, and 42 hours were designed to simulate the next pavement service periods of 0, 1, 2, 3, and 4 years after recycling, respectively.

Asphalt mastic produced by the colloid mill consisted of asphalt binder and limestone filler mixed at a mass ratio of 1:1. The optimum mixing quality in terms of filler distribution uniformity on the premise of equipment safety was obtained using the following conditions after several trials: 170°C, 35 minutes, and 500-1000 rpm. To determine the FAM weight composition, the AC-13 mixture typically used as the surface layer of asphalt pavements in China was selected. The FAM gradation was refigured based on 100% passing a certain 4.75-mm sieve.\textsuperscript{19} The optimum binder content of 8.2% was determined by the specific surface area method, in which it was assumed that each aggregate particle was homogeneously coated by the asphalt film with the thickness of 8 μm.\textsuperscript{21}

A Superpave gyratory compactor (SGC) was first used at the gyration number of 50 to fabricate the cylindrical FAM specimen with 100 mm in diameter and 70 mm in height. Each end of the SGC specimen was then sawed 10 mm due to the higher air void content. Finally, the beam specimen with 50 mm in height, 10 mm in width, and 10 mm in length was obtained for DSR tests by the high precision double-side saw.
2.3 | **Strain sweep test**

All tests were performed by the DSR AR 2000 instrument, as shown in Figure 1A. For asphalt binder and mastic, parallel plates of 8-mm diameter with a 2-mm gap were used. For FAM, the beam specimen was placed between 2 fixtures with the effective distance of 38.1 mm, as shown in Figure 1B. The strain sweep test was conducted on warm-mix recycled asphalt binder, mastic, and FAM to establish the LVE limits and strain levels used in fatigue tests. Loading cycles were applied with increasing the strain amplitude under a constant frequency. The complex shear modulus evolution with strain was recorded. The LVE strain range was considered as the strain within 10% complex shear modulus reduction. Testing conditions for the strain sweep test are listed in Table 1. Two replicates were conducted for each test.

2.4 | **Time sweep test**

The strain-controlled time sweep test was also conducted by DSR to characterize the fatigue resistance of warm-mix recycled asphalt materials in different scales. In the time sweep test, a cyclic sinusoidal loading corresponding to the fixed shear strain with no rest was applied to a specimen. The ratio of the change in the dissipated energy between successive cycles is a suitable indicator for fatigue life estimation of asphalt mixtures. A failure criterion based on this indicator was adopted in this study because it is of theoretic basis and more reasonable compared with the traditional criterion of the 50% reduction in initial stiffness. In this criterion, the loading cycle \( N_f \) corresponding to the turning point (intersection point of tangent lines) from the curve of the accumulative dissipated energy ratio \( DER \) (the ratio of the change in the dissipated energy between successive loading cycles to the dissipated energy of the previous cycles) vs loading cycle \( N \) was defined as the fatigue life, as shown in Figure 2. After several trials, the test was stopped at the 70% reduction in the complex shear modulus \( |G^*| \) to guarantee adequate testing time for calculating the fatigue life. Each test was performed at 3 shear strain levels to allow for determining the following fatigue model coefficients. The initial dissipated energy model was selected among different models based on the dissipated energy method after balancing the accuracy and convenience. Testing conditions for the time sweep test are also listed in Table 1. The shear strain levels beyond the LVE limits were determined to maintain the testing time in a

![Figure 1 Test instrument: A, DSR AR 2000 and B, beam specimen setup](Colour figure can be viewed at wileyonlinelibrary.com)

![A] DSR AR 2000  ![B] Beam specimen setup

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Test conditions</th>
</tr>
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<tbody>
<tr>
<td><strong>Material</strong></td>
<td><strong>Frequency (Hz)</strong></td>
</tr>
<tr>
<td>Binder</td>
<td>10</td>
</tr>
<tr>
<td>Mastic</td>
<td>10</td>
</tr>
<tr>
<td>FAM</td>
<td>10</td>
</tr>
</tbody>
</table>
reasonable and acceptable range. Two replicates were tested for each case.

\[ N_f = a(DE)^b \]  

(3)

In which \( N_f \) is fatigue life, \( DE \) is the initial dissipated energy density at the 50th loading cycle (kPa), and \( a \) and \( b \) are model coefficients.

3 | RESULTS AND ANALYSIS

3.1 | Strain sweep test results

Curves of complex shear modulus vs strain from the strain sweep test were plotted, respectively, for asphalt binder, mastic, and FAM with different ageing levels, as shown in Figures 3-5. The LVE strain range was calculated and shown in Figure 6. Figures 3-5 show that the complex shear modulus \( |G'| \) does not depend on strain level within the LVE range. When the strain exceeds a critical value (beyond the LVE range), \( |G'| \) rapidly decreases to almost zero, indicating the occurrence of material failure. Similar curve shapes can be obtained for asphalt binder and mastic, while FAM does not show a sudden stiffness decline due to the interlocking effect from fine aggregate particles. Figure 6 suggests that at the temperature of 20°C and the frequency of 10 Hz, the LVE strain upper limit is only sensitive to material scale and insensitive to ageing level and recycling plan. In either condition, the LVE strain ranges for asphalt binder, mastic, and FAM are basically within 3%, 0.8%, and 0.01%, respectively.

3.2 | Time sweep test results

Fatigue curves for asphalt materials in different scales were obtained from the time sweep test, as shown in Figure 7. The fatigue model based on the dissipated

FIGURE 2 Failure criterion definition [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 3 Curve of complex shear modulus vs strain for binder: A, plan 1, B, plan 2, and C, plan 3 [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 4  Curve of complex shear modulus vs strain for mastic: A, plan 1, B, plan 2, and C, plan 3 [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5  Curve of complex shear modulus vs strain for FAM: A, plan 1, B, plan 2, and C, plan 3 [Colour figure can be viewed at wileyonlinelibrary.com]
energy method as shown in Equation 3 can fit well to testing data. The coefficient of determination $R^2$ values for all cases are greater than 0.96.

### 3.3 Effect of ageing level

The average complex shear modulus $|G^*|$ during the LVE strain range obtained from the strain sweep test was selected as the stiffness indicator. The stiffening ratio, defined as the $|G^*|$ ratio before and after the secondary long-term ageing, was employed to evaluate the effect of ageing level. In other words, all $|G^*|$ values were normalized by the $|G^*|$ value with no ageing (PAV 0 hours) for comparison. Figure 8 indicates that the stiffening ratio linearly increases with the PAV ageing time in either case as expected. The curve slope difference among recycling plans is insignificant. Therefore, universal regression coefficients of the linear model can be obtained for different recycling plans. The slope only varies with material scale. Asphalt mastic has a much larger slope (0.026), followed by FAM (0.015) and binder (0.012).

The model coefficient $b$ shown in Equation 3 (fatigue curve slope on the log-log plot) is generally used to describe the fatigue performance of asphalt mixtures. The material with a lower $b$ value (a higher slope) is more sensitive to changes in the energy/strain, resulting in a poorer fatigue resistance. Figure 9 illustrates the effect of ageing level on the $b$ value. The $b$ value always decreases with the increase of the PAV ageing time regardless of material scale and recycling plan, indicating that the ageing behavior has a significantly negative effect of fatigue resistance for asphalt materials. The following linear regression equation is developed to characterize the correlation of the PAV ageing time $T_2$ and $b$.

$$b = c + dT_2 \quad (4)$$

In which $c$ and $d$ are regression coefficients, as listed in Table 2.

Similar conclusions can also be obtained from Figure 7. For example, after 42 hours, PAV ageing fatigue lives at different shear strain levels approximately fall to 1/7-1/6, 1/4-1/3, and 1/3-1/2 for asphalt binder, mastic, and FAM, respectively. It is should be mentioned that fatigue lives of recycled asphalt mixtures only achieve 40%-50% of that of the new asphalt mixtures when other material and testing conditions are same. It highlights that the warm-mix recycled asphalt pavement will face a more severe challenge from the fatigue cracking during the secondary service period, especially with a high RAP content.

The above phenomenon may be explained by the fact that each long-term ageing process involving the neat binder ageing and the SBS additive degradation leads to a continuous hardening of asphalt binder. Fatigue damage grows more rapidly as asphalt materials become harder. Adding the rejuvenator agent can only improve the compatibility of 4 different fractions for the neat binder, however, cannot recover the degraded SBS additive. The rheological property of the recycled binder is only partly recovered. Compared with the initial ageing process, the aromatics supplied by the rejuvenator agent is lost faster during the secondary ageing process, resulting in the faster stiffness increase and fatigue performance deterioration.

### 3.4 Effect of recycling plan

The average complex shear modulus $|G^*|$ values during the LVE strain range using different recycling plans are compared, as shown in Figure 10. Under a given ageing level in each scale, asphalt materials using the 3 recycling plans generally have the following ranking order in terms of stiffness (from high to low): plan 3, plan 2, and plan 1, which is particularly evident for asphalt binder. Similarly, Figure 9 shows that recycled asphalt materials using plan 1 rather than plan 2 or plan 3 obtain higher slope $b$ values, especially under a shorter PAV ageing time. Compared with using plan 2 or plan 3, fatigue lives of recycled asphalt materials using plan 1 improve by 0.8%-32.2% or 4.3%-70.0%, 14.3% or 34.2% on average. The statistically significant differences of $|G^*|$, $b$, and fatigue life among the 3 recycling plans are, respectively, confirmed by conducting an analysis of variance (ANOVA) at a 0.05 level of significance using the data analysis command of Microsoft Excel. All $F_{test}$ values (6.71, 8.34, and 23.96) are larger than the $F_{critical}$ of 3.34 or 3.10.
FIGURE 7  Fatigue curve for asphalt materials in different scales: A, plan 1, B, plan 2, and C, plan 3 [Colour figure can be viewed at wileyonlinelibrary.com]
Test results indicate that using WMA agent or SBR latex is beneficial to increase the material flexibility and fatigue resistance. The reason is that the WMA technique can significantly reduce the temperature requirements in the pavement construction process, such as mixing, paving, and compaction, which will greatly relieve the short-term ageing of asphalt mixtures. For recycled asphalt mixtures, it provides an effective flexibility compensation for the stiffer asphalt binder mainly from the high content RAP (85% in this study). This technique also ensures the volumetric property of recycled asphalt mixtures incompliance with the specification and production tolerance. All these contribute to the fatigue resistance improvement of warm-mix recycled mixtures.

By comparison of 2 additives, using SBR latex is more effective. In the micro level, it can effectively supply the lysed butadiene group due to the asphalt binder ageing and enhance the absorption peak strength of the group. In the macro level, with adding SBR latex the high-temperature stiffness of the aged asphalt binder increases; however, the intermediate-temperature and low-temperature stiffnesses decrease. The tensile strength, tensile strain, and fracture energy also significantly increase. It means that using SBR latex improves the rheological property and fatigue resistance of the recycled mixture without the sacrifice of the rutting resistance, which overcome the drawback of rejuvenator agent. In addition, although using SBR latex increases the viscosity of the recycled asphalt binder, it does not cause any compaction problem.

### 3.5 Performance correlation in different material scales

To quantitatively investigate the performance correlation of asphalt materials in different scales, 3 sets of data, respectively, measured from asphalt binder, mastic, and FAM were correlated pairwise by calculating the Pearson product moment correlation coefficient using the following equation.

\[ r = \frac{\text{cov}(x, y)}{\sqrt{D(x) + D(y)}} \]

In which \( r \) is correlation coefficient, \( x \) and \( y \) are 2 sets of data for analysis, \( \text{cov}(x, y) \) is covariance of \( x \) and \( y \), \( D(x) \) is variance of \( x \), and \( D(y) \) is variance of \( y \).

The average complex shear modulus \( |G'| \) during the LVE strain range was selected for stiffness correlation analysis, while the initial dissipated energy density \( DE \), model coefficient \( b \), and fatigue life \( N_f \) were selected for fatigue resistance correlation analysis. The \( r \) values for different data sets are provided in Table 3.

### Table 2 Regression coefficient of Equation 4

<table>
<thead>
<tr>
<th>Test</th>
<th>Plan 1</th>
<th></th>
<th></th>
<th>Plan 2</th>
<th></th>
<th></th>
<th>Plan 3</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>( c )</td>
<td>( d )</td>
<td>( R^2 )</td>
<td>( c )</td>
<td>( d )</td>
<td>( R^2 )</td>
<td>( c )</td>
<td>( d )</td>
<td>( R^2 )</td>
</tr>
<tr>
<td>Binder</td>
<td>-1.269</td>
<td>-0.007</td>
<td>0.897</td>
<td>-1.404</td>
<td>-0.004</td>
<td>0.873</td>
<td>-1.459</td>
<td>-0.002</td>
<td>0.763</td>
</tr>
<tr>
<td>Mastic</td>
<td>-1.701</td>
<td>-0.005</td>
<td>0.836</td>
<td>-1.703</td>
<td>-0.005</td>
<td>0.877</td>
<td>-1.752</td>
<td>-0.005</td>
<td>0.859</td>
</tr>
<tr>
<td>FAM</td>
<td>-2.088</td>
<td>-0.010</td>
<td>0.979</td>
<td>-2.257</td>
<td>-0.005</td>
<td>0.886</td>
<td>-2.256</td>
<td>-0.005</td>
<td>0.950</td>
</tr>
</tbody>
</table>
Table 3 shows that the $|G^*|$ values between mastic and FAM are highly correlated, and their correlation is much better than that between binder and mastic or between binder and FAM. It signifies that at the intermediate temperature the effect of filler properties on the material stiffness cannot be ignored and asphalt mastic is the critical material scale to distinguish the rheological property for different recycled mixtures. The findings do not agree with the other study mainly for the new HMA mixture in which the mixture stiffness could be calculated by the binder stiffness. The reason may be that the adhesion of asphalt binder and aggregates can be produced only after the forming of asphalt film adsorbed on the filler surface. In recycled mixtures, various types of additives and binder ageing level also have great effects on the interaction between asphalt binder and filler besides the property and content of filler itself. Therefore, it cannot simply predict the stiffness of recycled mixtures by the rheological property of asphalt binder.

Quite good correlations are observed in all cases of the DE value comparison, confirming the good ability of the dissipated energy method in capturing the driving force to create fatigue damage regardless of material scale. The energies of different types of asphalt mastic or FAM dissipated during the cyclic loading process can be predicted by the binder dissipated energy. Moreover, the nice fitting of Equation 3 to the time sweep test data implies that the fatigue resistance of asphalt materials can be accurately characterized by the dissipated energy method.

The slope $b$ values of FAM show fairly good correlations to those of binder or mastic, while a poor correlation exists between binder and mastic. The $b$ value characterizes the sensitivity of fatigue life to the dissipated energy variation in the fatigue model. The fatigue sensitivities of asphalt binder, mastic, and FAM are not very consistent, indicating the complex coupled effect of binder, filler, additives, and fine aggregates to resist the energy dissipated in the fatigue damage process.

Similar to the $|G^*|$ comparison, fatigue lives of mastic and FAM provide a much better correlation than those
of binder and mastic or binder and FAM, highlighting the important role that the filler plays in affecting the fatigue behavior of asphalt materials. Asphalt mastic is also confirmed as the critical material scale to evaluate the fatigue resistance for warm-mix recycled mixtures.

4 | CONCLUSIONS

Some important observations and conclusions made in this study are as follows:

- Material scale rather than ageing level or recycling plan (adding WMA agent or SBR latex) has a significant effect on the LVE strain range of warm-mix recycled asphalt materials.

- With the increase of the PAV ageing time, stiffness linearly increases and fatigue resistance significantly decreases regardless of material scale and recycling plan, indicating the negative effect and severe challenge caused by the secondary ageing for warm-mix recycled asphalt materials.

- Using WMA agent or SBR latex can improve the flexibility and fatigue resistance for recycled asphalt materials besides satisfying the volumetric property and compaction requirement.

- The fatigue model based on the dissipated energy method can accurately capture the fatigue performance of warm-mix recycled asphalt materials in different scales. The dissipated energies of mastic or FAM can be predicted by that of binder.

- Stiffness and fatigue resistance of FAM are only highly correlated to those of mastic, signifying that filler has an important effect and asphalt mastic is the critical material scale for stiffness and fatigue performance evaluation of warm-mix recycled asphalt materials at the intermediate temperature.

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