Title
Evaluation of mix design volumetrics and cracking potential of foamed Warm Mix Asphalt (WMA) containing Reclaimed Asphalt Pavement (RAP)

Journal
International Journal of Pavement Engineering, 23(10)

ISSN
1029-8436

Authors
Rahman, Mohammad Ashiqur
Zaman, Musharraf
Ali, Syed Ashik
et al.

Publication Date
2022-08-24

DOI
10.1080/10298436.2021.1902522

Evaluation of mix design volumetrics and cracking potential of foamed Warm Mix Asphalt (WMA) containing Reclaimed Asphalt Pavement (RAP)

Mohammad Ashiqur Rahman, Musharraf Zaman, Syed Ashik Ali, Rouzbeh Ghabchi & Sagar Ghos

INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING
https://doi.org/10.1080/10298436.2021.1902522

Evaluation of mix design volumetrics and cracking potential of foamed Warm Mix Asphalt (WMA) containing Reclaimed Asphalt Pavement (RAP)

Mohammad Ashiqur Rahman [a], Musharraf Zaman [b], Syed Ashik Ali [c], Rouzbeh Ghabchi [d] and Sagar Ghos [c]

[a]School of Civil and Environmental Engineering, The University of California, Davis, CA, USA; [b]School of Civil Engineering and Environmental Science, Mewbourne School of Petroleum and Geological Engineering, The University of Oklahoma, Norman, OK, USA; [c]School of Civil Engineering and Environmental Science, The University of Oklahoma, Norman, OK, USA; [d]Department of Civil and Environmental Engineering, South Dakota State University, Brookings, SD, USA

ABSTRACT
In this study, the mix design volumetrics and cracking potential of foamed Warm Mix Asphalt (WMA) containing various amounts of Reclaimed Asphalt Pavement (RAP) were evaluated. It was found that the increased coating ability of the foamed WMA binder counteracted the lowering of mixing and compaction temperatures for WMA. Therefore, both control HMA and foamed WMA exhibited similar mix design volumetrics up to certain lower temperatures. However, further reductions in the mixing and compaction temperatures for foamed WMA were found to exhibit improper mixing between aggregates and foamed binder. Despite foamed WMA exhibiting similar volumetric properties as HMA up to certain lower temperature, their fatigue cracking performance was found to be significantly different. The foamed WMA was found to exhibit higher cracking resistance compared to HMA in Louisiana Semi-Circular Bending (SCB) and Illinois Flexibility Index Test (I-FIT) tests. A similar trend in the cracking resistance was observed for coarser mixes in the Abrasion Loss Test (commonly known as Cantabro test). However, the Cantabro test could not screen finer mixes for their cracking resistance as it lacks a mechanistic basis. Finally, the foamed WMA technology was found to increase the cracking resistance of asphalt mixes. The higher RAP content in the foamed WMA, on the contrary was found to lower the cracking resistance of asphalt mixes due to incorporation of aged and stiffer binder from RAP.

ARTICLE HISTORY
Received 12 June 2020
Accepted 8 March 2021

KEYWORDS
Foamed warm mix asphalt (WMA); dynamic modulus; percent air voids; J_c value; flexibility index (FI); percent abrasion mass loss (ML)

Introduction

As a part of effort toward establishing a sustainable and eco-friendly asphalt pavement, Warm Mix Asphalt (WMA) technologies with Reclaimed Asphalt Pavement (RAP) can be considered as a viable candidate. About two decades ago, the WMA technologies were introduced for producing asphalt mixes at a lower production temperature (about 30°C) than traditional Hot Mix Asphalt (HMA) (Jones 2004, Prowell *et al.* 2007, Rubio *et al.* 2012). Generally, WMA technologies reduce the viscosity of asphalt binder by using chemical additives, organic additives, and water-based or water-containing foaming processes and lower the mixing and compaction temperatures for asphalt mixes (Bonaquist 2011, Alhasan *et al.* 2014, Kheradmand *et al.* 2014). As a result, major savings in fuel cost, reduction in gas emission, and better workability of mixes are achieved during construction of asphalt pavements (Jones 2004, Prowell *et al.* 2007, Rubio *et al.* 2012). Among the current WMA technologies, the plant foaming technique (called 'foamed WMA' in this study) has gained the most attention as it eliminates the need for chemical additives for production of asphalt mixes (Jenkins 2000). Also, among various recycled materials, RAP is the most widely used recycled material by the asphalt industry (Al-Qadi *et al.* 2015). The availability of binder in RAP reduces the amount of virgin binder needed in producing asphalt mixes. Also, incorporation of RAP in asphalt mixes lowers the construction costs and preserves environmental resources by reducing the demand for new aggregate (Jones 2008, Ghabchi 2014, Al-Qadi *et al.* 2015). Although use of RAP in foamed WMA has several economic and environmental benefits, studies have expressed some concerns about the pavement performance (Shu *et al.* 2008, Bonaquist 2011, Goh and You 2011, Zhao *et al.* 2013).

A lower mixing temperature of WMA than HMA can be responsible for partially dried aggregates and can result in a weaker bond between the asphalt binder and aggregates (Hurley and Prowell 2006, Prowell *et al.* 2007, Ali *et al.* 2013). Furthermore, while using RAP in WMA, the blending of aged binder from RAP and new binder may be hindered due to the low mixing and compaction temperatures of WMA (Bonaquist 2011). The amount of total blended binder (commonly known as active binder) mainly controls the mix design of asphalt mixes (Roberts et al. 1991). Therefore, evaluation of mix design volumetrics of foamed WMA with different RAP contents is necessary to avoid potential problems.

Currently, no distinct mix design procedure is available for foamed WMA containing RAP. Several factors, namely aggregate gradation, binder content, number of gyration, mixing and compaction temperatures, RAP binder grade and proper mixing of aged binder from RAP with virgin binder influence the design of asphalt mixes (Roberts et al. 1991). The current

CONTACT Mohammad Ashiqur Rahman mohrahman@ucdavis.edu

state of the art for WMA mix design involves preparing a mix using HMA design procedure following the AASHTO R 35 method (AASHTO 2013). The same method is then used for the production of foamed WMA in an asphalt plant without making modifications to the mix design and using a foaming technology (Bonaquist 2011). Also, most asphalt mix design laboratories do not own a laboratory foamer to produce foamed binder. As a result, designs of foamed WMA, including those containing RAP, are generally performed using the corresponding designs of HMA containing RAP without using a foamer. However, a combination of RAP and low production temperature for WMA may lead to mixes that are more temperature sensitive compared to HMA (Bonaquist 2011). Therefore, foamed WMA containing RAP may exhibit significantly different distresses in the field compared to traditional HMA.

Fatigue cracking is one of the commonly observed distresses in asphalt pavements caused by thermal gradients and traffic loading (Colombier 2004, Baek 2010, Kim *et al.* 2012, Al-Qadi *et al.* 2015, Ozer *et al.* 2016). Currently, there is no general agreement on a single test method for evaluating the fatigue resistance of asphalt mixes (Barman *et al.* 2018). Different agencies are following different test methods in characterising the cracking resistance of asphalt mixes. Both Louisiana Semi-Circular Bending (SCB) and Illinois SCB, commonly known as Illinois Flexibility Index Test (I-FIT), are used by some state Departments of Transportation (DOTs) for evaluating the fracture performance of asphalt mixes (Kim *et al.* 2012, NAPA 2015, Ozer *et al.* 2016). Also, some transportation agencies are using Abrasion Loss Test (commonly known as Cantabro test) to evaluate the cracking potential of asphalt mixes (NAPA 2015, NCAT 2017). However, significant differences in screening of asphalt mixes for fatigue cracking may be observed while considering different test methods (Barman *et al.* 2018). At present, the fatigue cracking performance data for WMA containing RAP, particularly for a high amount of RAP, are lacking. The present study is expected to fill this gap by generating laboratory performance data for WMA and HMA containing a high amount of RAP. The specific objectives of this study are given below:

(i) Evaluate and compare the mix design volumetrics of foamed WMA and HMA containing the same amount of RAP;
(ii) Evaluate and compare the fatigue cracking performance of foamed WMA and HMA containing the same amount of RAP.

Materials and methods

Materials

Two types of aggregate gradations, a coarser S3 gradation (Nominal Maximum Aggregate Size (NMAS) = 19.0 mm) and a finer S4 gradation (NMAS = 12.5 mm), were selected for this study. The asphalt mixes with S3 aggregate gradation (called herein S3 mixes) were prepared with 25% RAP, whereas the asphalt mixes with S4 aggregate gradation (called herein S4 mixes) were prepared with 5% RAP, following the current Department of Transportation (DOT) specification (ODOT 2013). A PG 64-22 asphalt binder was used as the virgin binder in producing the HMA. Figure 1 presents the G*/sin δ vs. temperature plot for both PG 64-22 virgin binder and extracted RAP binder. The RAP binder was extracted and recovered using the AASHTO T 164 and ASTM D 5404 test procedures, respectively. As expected, the RAP binder was showing much higher G*/sin δ values compared to those of the virgin binger for both unaged and RTFO aged conditions. The continuous high-temperature PG of the virgin binder and extracted RAP binder were found to be 66.2°C and 94.1°C,

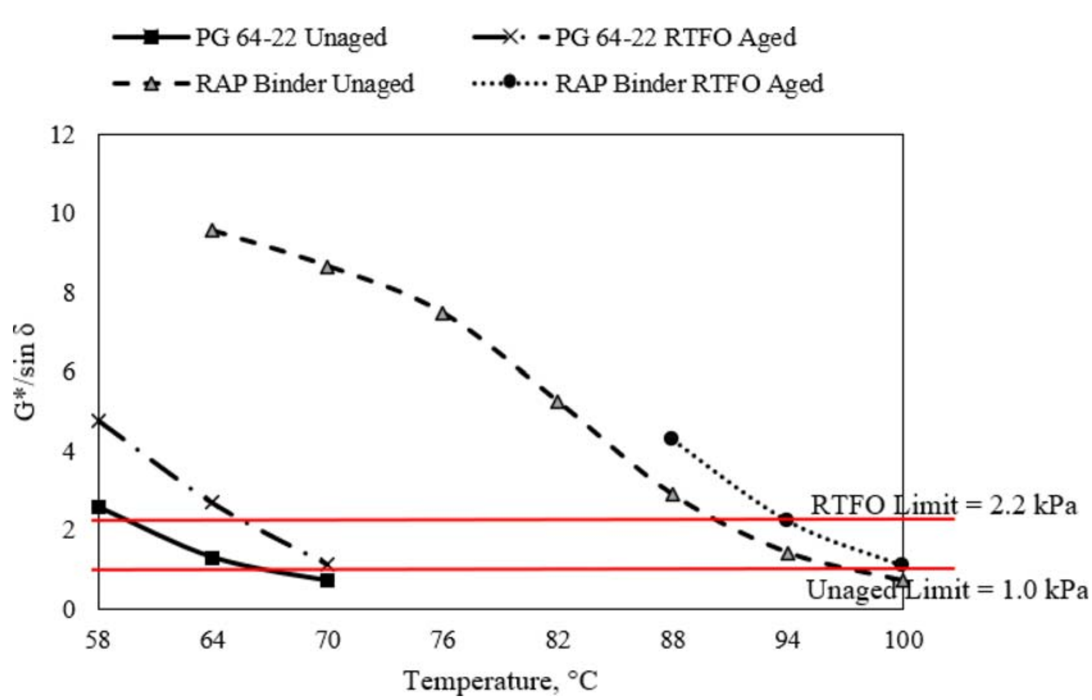

Figure 1. G*/sin δ vs. temperature plot for virgin and RAP binder.

respectively. From the viscosity-temperature relationship of the virgin binder, the mixing and compaction temperatures for HMA were used as 163°C and 149°C, respectively. However, to produce WMA, the collected PG 64-22 binder was foamed using a laboratory foamer, called Accufoamer. Figure 2 presents a schematic diagram of the foaming mechanism for Accufoamer. This foamer has two tanks: one for asphalt binder and the other for water as the foaming agent (Figure 2). The temperature and pressure used for generating foamed binder were 135°C and 210 kPa, respectively. These parameters were selected based on the current practice followed by the local asphalt plants and the literature (Bonaquist 2011, Malladi 2015). Foaming asphalt binder was produced by injecting pressurised water into the preheated liquid asphalt binder producing steam, leading to an increase in the volume of binder and a reduction in viscosity (Jenkins 2000). The current practice of mixing and compaction temperature to produce foamed WMA in the asphalt plant are 135°C and 127°C, respectively.

In this study, a total of eight asphalt mixes were produced in the laboratory. The characteristics of these eight mixes are summarised in Table 1. Mix-1 through Mix-4 were prepared using S3 gradation while Mix-5 through Mix-8 were prepared using S4 gradation. Mix-1 and Mix-5 were prepared following the HMA design procedure at higher mixing (163°C) and compaction (149°C) temperatures. These mixes used virgin binder (without foaming) and are considered control mixes. Mix-2 and Mix-6 were prepared with foamed binder in the laboratory using lower temperatures, 135°C for mixing and 127°C for compaction. These temperatures were selected based on the previous studies conducted on foamed WMA technology and current practice in the asphalt plant (Bonaquist 2011, Malladi 2015). For preparing foamed WMA, aggregates and RAP were dried at a lower temperature (135°C) for two hours, which is commonly used in the WMA production plant.

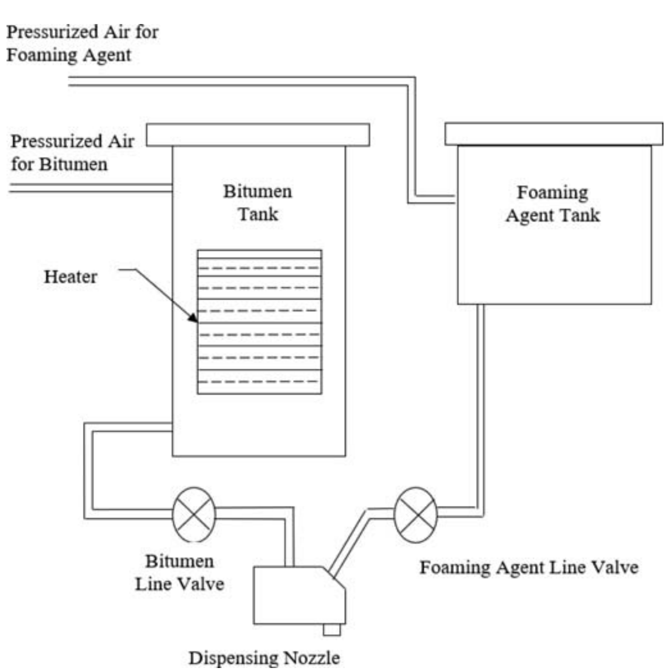

Figure 2. Schematic diagram AccuFoamer used in this study.

Table 1. Properties of the asphalt mixes.

Mix ID	Mix type	Mixing/ compaction temperatures (°C)	NMAS (mm)	Virgin binder grade	Foamed binder	RAP content (%)
Mix-1	HMA S3	163/149	19	PG 64-22	No	25
Mix-2	WMA S3	135/127	19	PG 64-22	Yes	25
Mix-3	WMA S3	115/107	19	PG 64-22	Yes	25
Mix-4	WMA S3	95/87	19	PG 64-22	Yes	25
Mix-5	HMA S4	163/149	12	PG 64-22	No	5
Mix-6	WMA S4	135/127	12	PG 64-22	Yes	5
Mix-7	WMA S4	115/107	12	PG 64-22	Yes	5
Mix-8	WMA S4	95/87	12	PG 64-22	Yes	5

To evaluate the effect of reduction in mixing and compaction temperatures on volumetric properties, the mixing and compaction temperatures were reduced to 115°C and 107°C, respectively, for both Mix-3 and Mix-7. The mixing and compaction temperatures for both Mix-4 and Mix-8 were further reduced to 95°C and 87°C, respectively. For all mixes, aggregates and RAP were heated at the corresponding mixing temperatures for two hours. The foamed binder was produced at 135°C for all cases.

Volumetric properties

The design method mentioned in the AASHTO R 35 is primarily based on the volumetric properties i.e. Air Voids (AV), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) of the asphalt mixes (AASHTO 2013). Aggregate gradations, such as S3 and S4 gradations, are maintained in a way to satisfy the AASHTO R 35 limits for VMA and VFA (AASHTO 2013). Therefore, the volumetric properties of asphalt mixes are generally dictated by the percent air voids at desired number of gyrations (Zhao *et al.* 2012). In this study, the optimum binder content was determined based on the target four percent air voids and by satisfying requirements for VMA and VFA. The optimum binder contents for Mix-1 and Mix-5 were found as 4.5% and 4.9% by weight of total mix, respectively. The amount of binder replaced by RAP for Mix-1 and Mix-5 were found to be 31.1% and 4.1%, respectively. Also, for calculating the percent air voids of asphalt mixes, theoretical maximum specific gravity (G_{mm}) and bulk specific gravities (G_{mb}) of asphalt mixes were determined in according to AASHTO T 209 and AASHTO T 166 methods, respectively (AASHTO 2010, AASHTO 2012). A total of 50 gyrations was used in the Superpave® Gyratory Compactor (SGC), to compact asphalt samples considering light traffic condition and to obtain a final height of 115 ± 5 mm. The percent air voids were then calculated using the following formula:

$$\%\ \text{Air Voids} = \frac{G_{mm} - G_{mb}}{G_{mm}} * 100\% \quad (1)$$

The average percent air voids for volumetric samples of Mix-2 (WMA S3) and Mix-6 (WMA S4) were compared with Mix-1 (control HMA S3) and Mix-5 (control HMA S4), respectively. For each mix type at least three volumetric samples were prepared to check the repeatability of test results. Two-tail *t*-tests were conducted to identify the statistical difference of average percent air voids between WMA and HMA samples, at 95% confidence level. The optimum binder content was adjusted for WMA, if significant statistical differences were observed.

Effect of further reduction in temperature was investigated using two-tail *t*-tests by identifying differences in percent air voids between WMA samples (Mix-3, Mix-4, Mix-7, and Mix-8) and control HMA samples (Mix-1 and Mix-5). The average percent air voids of Mix-3 and Mix-4 were compared with control Mix-1, whereas the average percent air voids of Mix-7 and Mix-8 were compared with control Mix-5. Recommendations on mixing and compaction temperatures for foamed WMA were provided based on these statistical results.

Laboratory performance tests

Sample preparation

Asphalt samples for all performance tests were prepared in the laboratory using the Superpave® Gyratory Compactor (SGC). After mixing, bulk HMA was short-term aged at 135°C for 4 h as per AASHTO R 30 to simulate the conditioning of plant-produced mixes (AASHTO 2002). As suggested by Bonaquist (2011), the bulk WMA was short-term aged at WMA compaction temperature (127°C) for 2 h to simulate the field conditioning during WMA production. After the compaction, volumetric tests were conducted to check air voids in accordance with AASHTO T 166 (AASHTO 2010). The target air voids were kept at 7 ± 0.5% based on the densities typically obtained in the field (AASHTO 2010).

Dynamic modulus (DM) test

Dynamic modulus tests were conducted as per AASHTO T 378 using an Asphalt Mixture Performance Tester (AMPT) (AASHTO 2017). For this purpose, over-sized samples with a diameter of 150 mm and a height of 167.5 mm were prepared using SGC. These samples were then cored from the center to obtain specimens having a diameter of 100 mm. The cored specimens were cut at both ends using a heavy duty saw to obtain specimens with a height of 150 mm. As suggested by Chehab *et al.* (2000), this method produces specimen with uniform air voids in both vertical and radial directions. For each asphalt mix, three replicates were prepared for dynamic modulus testing.

The dynamic modulus tests were conducted at four different temperatures, namely 4.4°, 21.1°, 37.8°, and 54.4°C with six loading frequencies of 25, 10, 5, 1, 0.5 and 0.1 Hz at each temperature. The applied loading consisted of a sinusoidal compressive (haversine-shaped) pulse. The load magnitude was adjusted based on the material stiffness, frequency and temperature, to keep the strain response within 50–150 micro-strains. Also, for this study, dynamic modulus tests were performed under unconfined condition (AASHTO 2017). Finally, master curves were developed using the time-temperature superposition principle at a reference temperature of 21.1°C. A sigmoidal function was used in fitting the master curve, as shown in Equation (2) (Singh 2011).

$$\log|E^*| = \delta + \frac{\alpha}{1+\exp(\beta+\gamma(\log f_r))} \quad (2)$$

where: $|E^*|$, dynamic modulus (MPa); f_r, reduced frequency at reference temperature; δ, minimum value of $|E^*|$; $\delta + \alpha$, maximum value of $|E^*|$; and β, γ, parameters describing the shape of the sigmoidal function.

The general form of the shift factor used is given in Equations (3) and (4).

$$a(T) = \frac{f_r}{f} \quad (3)$$

$$\log(f_r) = \log(a(T)) + \log(f) \quad (4)$$

where: $a(T)$, temperature shift factor; T, temperature (°C); and f, frequency at a particular temperature.

A nonlinear optimisation program (Solver) in Microsoft Excel was used for solving the master curve coefficients, namely α, β, γ, δ and c. Then, a quadratic polynomial fit, as shown in Equation (5), was used to establish the shift factor-temperature relationship.

$$\log(a(T)) = mT^2 + nT + p \quad (5)$$

where: T, temperature (°C); and m, n, p, polynomial fitting curve coefficients.

Louisiana semi-circular bend (SCB) test

In this study, the Louisiana SCB tests were conducted following ASTM D 8044 (ASTM, 2013). In this method, the fracture resistance of asphalt mixes is evaluated based on the elasto-plastic fracture mechanics concept using critical strain energy release rate (Kim *et al.* 2012). These tests were conducted on semi-circular-disk-shaped specimens having a diameter of 150 mm and a thickness of 50 mm. At first, samples having a diameter of 150 mm and a height of 120 mm were prepared using SGC. Then each sample was saw cut to produce four semi-circular specimens with a diameter of 150 mm and a thickness of 50 mm. The Louisiana SCB tests were conducted on specimens with three different notch depths, namely 25.4, 31.8, and 38.0 mm. For each notch depth, three replicate specimens were tested to check the repeatability of test results.

The Louisiana SCB test method characterises the cracking resistance of asphalt mixes at an intermediate temperature (25°C in this study) in terms of critical strain energy release rate or *J-integral* (J_c) defined by Equation 6. As shown in Figure 3, specimens were loaded monotonically at 0.5 mm/min using a three-point flexural apparatus (Kim *et al.* 2012). The average strain energy up to failure was determined for each notch depths and was considered for further analysis. The rate of change in average strain energy with respect to notch depths was then determined using the slope of average strain energy (U) vs. notch depth (a) line. The rate of change was divided by the thickness of the specimen (b) to obtain the J_c value. A higher *J-integral* value represents a specimen with higher resistance to fatigue cracking (Kim *et al.* 2012).

$$J_c = -\left(\frac{1}{b}\right)\frac{dU}{da} \quad (6)$$

where: J_c, critical strain energy release rate (kJ/m^2); b, SCB specimen thickness (m); a, notch depth (m); and U, strain energy (area under stress–strain curve up to failure) (N-m).

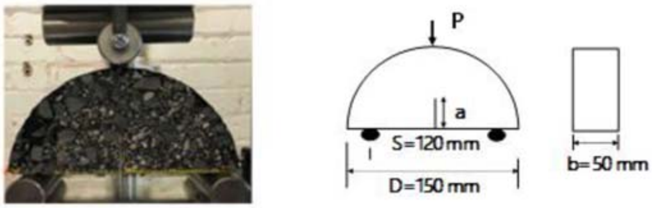

Figure 3. Test setup for semi-circular bending (SCB) testing.

Illinois flexibility index (I-FIT) test

In addition to Louisiana SCB test, Illinois SCB test method, also known as I-FIT test, was used to evaluate the cracking potential of asphalt mixes. This test was conducted in accordance with AASHTO TP 124 test method (AASHTO 2016b). This method requires specimens with only one notch depth (15 mm) and utilises a much faster loading rate (50 mm/min). Sample preparation was similar to that used in the Louisiana SCB method, except the notch width was much smaller (1.50 ± 0.05 mm), as per Al-Qadi *et al.* (2015). A saw with appropriate blade width was used to create this notch. The prepared specimens were tested at 25°C. The fatigue cracking resistance of the asphalt mixes were determined using Flexibility Index (FI), which accounted for post-crack performance (Al-Qadi *et al.* 2015). As noted by Al-Qadi *et al.* (2015), the FI can be expressed by Equation (7). The total area under the load-displacement curve was considered in calculating FI, as shown in Figure 4. The determination of FI also depends on post-peak slope (m) and critical displacement (u_i). The post-peak slope is defined as the slope at the inflection point after peak load in the load-displacement diagram (Figure 4). The displacement at which post-peak slope intersects the displacement axis is termed critical displacement (u_i).

$$FI = A * \frac{G_{fa}}{abs(m)} \tag{7}$$

where: A, unit conversion factor (0.01); G_{fa}, total fracture energy (Joules/m^2); Abs, absolute value; and m, post-peak slope (kN/mm).

Abrasion loss test (Cantabro test)

Along with Louisiana and Illinois SCB tests, Abrasion Loss Test (commonly known as Cantabro Test) was used to evaluate cracking resistance of asphalt mixes in accordance with AASHTO TP 108 (Abuawad *et al.* 2015). Samples with a diameter of 150 mm a height of 115 ± 5 mm, and an air void of 7 ± 0.5% were prepared using SGC, for this purpose. At least three replicate samples were prepared for verifying the reproducibility of test results.

The prepared samples were tested using a Los Angeles Abrasion machine without the steel spheres. Before conducting the test, the samples were conditioned at 25°C for 4 h. The drum of the Los Angeles machine was turned 300 times at 30 to 33 revs/min. The percent abrasion Mass Loss (ML) was calculated using Equation 8. The recommended maximum abrasion loss suggested by NCAT for asphalt mixes was 20% (NCAT 2017).

$$ML = \frac{W_1 - W_2}{W_1} * 100 \tag{8}$$

where W_1, initial mass of the sample (g); and W_2, final mass of the sample (g).

Results and discussion

Volumetric properties

Figure 5 and Table 2 present the results for average percent air voids for all S3 mixes (Mix-1, Mix-2, Mix-3, and Mix-4) containing 25% RAP. Both Mix-1 and Mix-2 were found to exhibit similar volumetric properties with an average percent air voids of 4.2% for both mixes. The corresponding standard deviations for Mix-1 and Mix-2 were found to be 0.1% and 0.2%, respectively. The t-value obtained from the two-tail t-test for Mix-2 compared to Mix-1was 0.6. Also, the p-value was found to be 0.58, which is greater than 0.05. Therefore, it is evident that the difference in percent air voids between Mix-1 and Mix-2 is insignificant, at 95% confidence level. Similar volumetric properties for both HMA and WMA were reported by Bonaquist (2011), when the absorbed binder content is less than one percent. For S3 mixes, the percent absorbed binder was found to be 0.42%, which is less than 1.00%. An increase in coating ability of binder due to foaming process is expected to counteract the lowering of mixing and compaction temperatures for WMA (Jones *et al.* 2010, Bonaquist

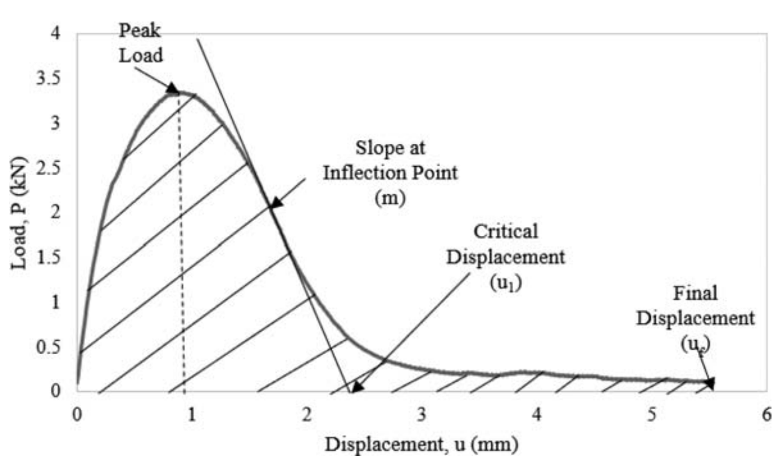

Figure 4. A typical outcome of the Illinois-SCB test (After Al-Qadi *et al.*, 2015).

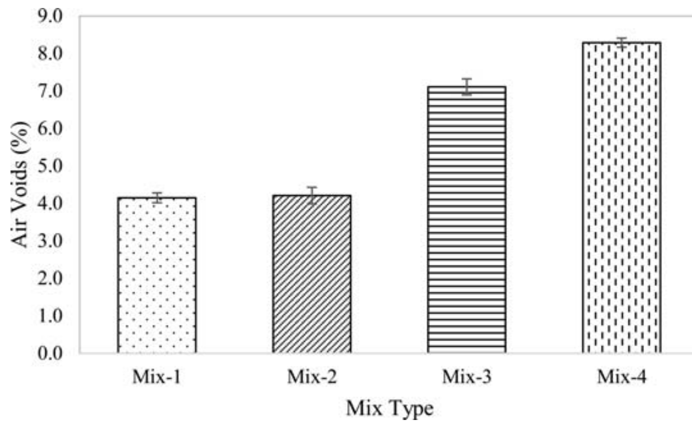

Figure 5. Percent air voids for S3 mixes.

2011). Therefore, compaction effort required for both HMA (Mix-1) and foamed WMA (Mix-2) samples are expected to be similar. A number of other studies have reported similar finding (Hurley and Prowell 2006, Prowell *et al.* 2007, Jones *et al.* 2010, Malladi 2015).

While using RAP in WMA, the blending of aged binder from RAP and virgin binder may be hindered due to the lower mixing and compaction temperatures of WMA than HMA (Bonaquist 2011). To ensure adequate blending of aged and virgin binders, the compaction temperature of WMA should be greater than the high-temperature PG of RAP (Bonaquist 2011). The continuous high-temperature PG of the extracted RAP binder used in this study was found to be 94.1°C. The Dynamic Shear Rheometer (DSR) test according to AASHTO T 315 was used to determine the high-temperature PG of the RAP binder (AASHTO 2018). As the volumetric samples of Mix-2 were compacted at a higher temperature (127.0°C) than the high-temperature PG of the RAP binder (94.1°C), proper blending of aged and virgin binder was expected for foamed WMA. Therefore, it is expected that the difference in percent air voids between Mix-1 and Mix-2 samples would be insignificant, as was the case here. Hence, it is postulated that the foamed WMA S3 containing 25% RAP can be designed as per AASHTO R 35 (AASHTO 2013), when mixing and compaction temperatures are kept at 135°C and 127°C, respectively.

However, the percent air voids were found to increase with further reduction in mixing and compaction temperatures for foamed WMA. Two-tail *t*-tests were performed to identify statistical differences in air voids between Mix-1 and foamed WMA with reduced mixing and compaction temperatures (Mix-3 and Mix-4). The corresponding results are summarised in Table 2. The *t*- values observed for Mix-3 and Mix-4 were 22.2 and 46.7, respectively, compared to Mix-1. These values were much higher compared to the *t*-value obtained for Mix-2 compared to Mix-1 (0.6). Also, the *p*-values observed for Mix-3 and Mix-4 were 2.936e-04 and 3.679e-07, respectively. These *p*-values were much lower than 0.05 for both cases indicating that the percent air voids of mixes with reduced mixing and compaction temperatures were significantly different than those of the control HMA, at the 95% confidence level. Furthermore, the standard errors were found to be very small (0.1) for all three *t*-tests. This is indicating higher reliability on the *t*-test results. Therefore, it can be concluded that the mixing and compaction temperatures significantly control the volumetric properties of foamed WMA. Also, differences in percent air voids of Mix-4 samples became more significant compared to Mix-1 samples when the mixing and compaction temperatures were reduced by 40°C (from the current WMA practice), while keeping the amount of RAP content unchanged (25%). This is due to low amount of active binder obtained from RAP at these low mixing and compaction temperatures. For S3 mixes with 25% RAP content, about 31% of the total binder was expected to be replaced by the RAP binder. As the compaction temperature (87.0°C) for Mix-4 was lower than the high-temperature PG of the extracted RAP binder (94.1°C), sufficient active binder from RAP was likely not achieved.

A similar trend in percent air voids of foamed WMA S4 mixes was observed as compared to control HMA S4 mix. Figure 6 and Table 3 present the percent air voids results for

Table 2. A Summary of statistical results for S3 mixes.

Mix ID	Mix type	RAP content (%)	Mixing/compaction temperature (°C)	Average air voids (%)	*t*-Value (two-tail *t*-test)	Standard error, SE	*p*-Value (two-tail *t*-test)	Difference at 95% confidence level
Mix-1	HMA	25	163/149	4.2			Control mix	
Mix-2	WMA	25	135/127	4.2	0.6	0.1	0.58	Insignificant
Mix-3	WMA	25	115/107	7.1	22.2	0.1	2.936e-04	Significant
Mix-4	WMA	25	95/87	8.3	46.7	0.1	3.679e-07	Significant

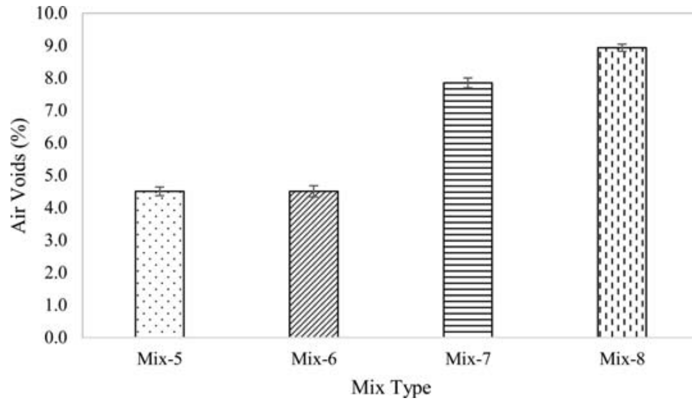

Figure 6. Percent air voids for S4 mixes.

all S4 mixes (Mix-5, Mix-6, Mix-7, and Mix-8) containing 5% RAP. The average percent air voids for both Mix-5 and Mix-6 were observed as 4.5% (Table 3). The standard deviations of percent air voids for Mix-5 and Mix-6 were 0.1% and 0.2%, respectively. The *p*-value obtained for the difference between Mix-5 and Mix-6 was 0.98, which is much higher than 0.05. Therefore, both Mix-5 and Mix-6 were found to show similar volumetric properties, as expected. However, the *t*-values observed for Mix-7 and Mix-8 compared to control Mix-5 were 24.9 and 37.3, respectively (Table 3). These values were relatively large compared to *t*-value obtained for Mix-6 (0.1). Also, the standard error values of the two-tail *t*-tests were found to vary between 0.0 and 0.1 for all three cases, as shown in Table 3. Furthermore, the *p*-value observed for Mix-7 and Mix-8 were 1.75e-05 and 1.571e-05, respectively. These *p*-values are much lower than 0.05 for both cases, which indicates that the percent air voids of mixes with reduced mixing and compaction temperatures are significantly different than those of the control HMA, at the 95% confidence level. An increase in percent air voids was observed with a decrease in mixing and compaction temperatures because of difficulty in compaction. Also, the difference in percent air voids between Mix-5 and Mix-8 became larger, as expected. The low compaction temperature (87.0°C) of Mix-8 than the high-temperature PG of RAP binder (94.1°C) is responsible for this phenomenon.

As foamed WMA (Mix-3, Mix-4, Mix-7 and Mix-8) with lower mixing and compaction temperatures exhibited statistically significant difference in volumetric properties compared to those of control HMA, these were not considered for further analysis. Cracking performances of foamed WMA (i.e. Mix-2 and Mix-6) mixed at 135°C and compacted at 127°C were evaluated in the laboratory and compared to their HMA counterparts (i.e. Mix-1 and Mix-5).

Cracking resistance

Dynamic modulus test

Figure 7(a) and (b) present the dynamic modulus master curves at 21.1°C temperature for S3 mixes (Mix-1 and Mix-2) and S4 mixes (Mix-5 and Mix-6), respectively. An increase in dynamic modulus values was observed with an increase in frequency and decrease in test temperature. These results are compatible with expectations as an increase in testing frequency and/or a decrease in temperature increases the stiffness of asphalt mixes (Copeland *et al*. 2010, Goh and You 2011, Singh 2011, Ghabchi 2014).

Also, both HMA and foamed WMA showed a similar trend in the dynamic modulus master curve (Figure 7). However, relatively lower dynamic modulus values were observed for foamed WMA mixes (Mix-2 and Mix-6) compared to their HMA counterparts (Mix-1 and Mix-5). For example, at 10^{-4} Hz reduced frequency, predicted dynamic modulus values found for Mix-1 (control HMA S3) and Mix-2 (WMA S3) were 249 and 147 MPa, respectively. A similar trend was observed for S4 mixes. The predicted dynamic modulus values found for Mix-5 (control HMA S4) and Mix-6 (WMA S4) at 10^{-4} Hz reduced frequency were 151 and 120 MPa, respectively. Therefore, Mix-2 and Mix-6 are expected to show lower stiffness compared to Mix-1 and Mix-5, respectively. A lower degree of aging in WMA is expected to reduce the mix stiffness compared to HMA. Several other researchers also reported lower dynamic modulus values for WMA compared to control HMA (Copeland *et al*. 2010, Goh and You 2011, Singh 2011, Ghabchi 2014). A lower dynamic modulus is expected to cause less fatigue cracking for foamed WMA (Ghabchi 2014). It is also evident that both S3 mixes (Mix-1 and Mix-2) containing 25% RAP exhibited higher dynamic modulus values

Table 3. A Summary of statistical results for S4 mixes.

Mix ID	Mix type	RAP content (%)	Mixing/compaction temperature (°C)	Average air voids (%)	*t*-Value (two-tail *t*-test)	Standard error, SE	*p*-Value (two-tail *t*-test)	Difference at 95% confidence level
Mix-5	HMA	5	163/149	4.5	Control mix			
Mix-6	WMA	5	135/127	4.5	0.1	0.0	0.98	Insignificant
Mix-7	WMA	5	115/107	7.9	24.9	0.1	1.75e-05	Significant
Mix-8	WMA	5	95/87	8.9	37.3	0.1	1.571e-05	Significant

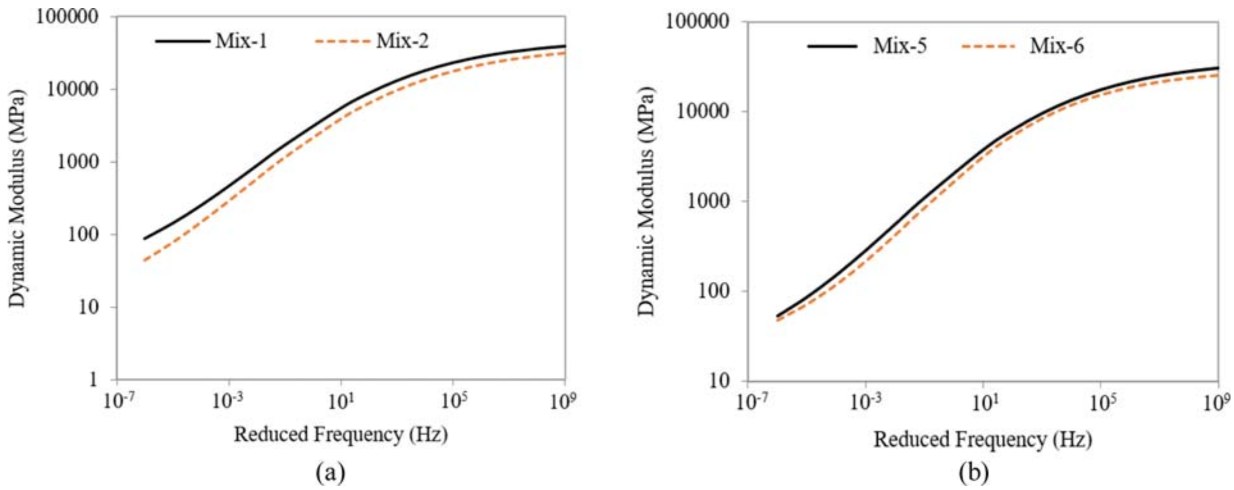

Figure 7. Master curves at 21.1°C reference temperature for (a) S3 mixes and (b) S4 mixes.

compared to S4 mixes (Mix-5 and Mix-6) containing 5% RAP at 10^{-4} Hz reduced frequency. As reported by Ghabchi (2014), higher RAP contents lead to stiffer mixes and higher dynamic modulus, which supports the results obtained from this study.

Louisiana SCB test

Figure 8(a) and (b) show the J_c values for S3 and S4 mixes, respectively. The foamed WMA was found to exhibit higher J_c values compared to HMA (Figure 8). The asphalt mixes with higher J_c value is expected to show higher resistance to cracking (Kim *et al.* 2012). The J_c values for Mix-1 and Mix-2 were found to be 0.35 and 0.46 kJ/m^2, respectively. A similar trend was also followed by S4 mixes containing 5% RAP. The J_c values for Mix-5 and Mix-6 were found to be 0.39 and 0.60 kJ/m^2, respectively. As noted earlier, lower mixing and compaction temperatures for WMA are expected to produce more flexible mixes due to reduced aging (Hurley and Prowell 2006, Alhasan *et al.* 2014, Malladi 2015). This may have resulted in a higher cracking resistance for foamed WMA (Kim *et al.* 2012, Zhao *et al.* 2013, Dong *et al.* 2017). According to ASTM D 8044, a J_c value of 0.5 to 0.60 kJ/m^2 ensures sufficient cracking resistance for a mix (ASTM, 2013). It is evident from Figure 8 that Mix-1, Mix-2 and Mix-5 had lower J_c values than the minimum requirement. Mix-2 did not satisfy the minimum requirement only by a small margin (0.03 kJ/m^2). However, Mix-6 satisfied the ASTM D 8044 minimum requirement for J_c value (ASTM, 2013).

A comparison of J_c values indicated higher cracking resistance for S4 mixes than S3 mixes. This may be attributed to significantly higher RAP content (25%) of S3 mixes than S4 mixes (5%). According to a number of studies, incorporation of RAP up to a certain limit has a positive effect on the cracking resistance of asphalt mixes (McDaniel *et al.* 2000, Huang *et al.* 2004, Ghabchi *et al.* 2016). Also, finer mixes (S4 mixes) are expected to show a higher resistance to cracking than coarser mixes (S3 mixes) due to difference in crack propagation mechanisms (Barman *et al.* 2018). In case of a coarser mix, crack generally propagates within the mastic (composed of asphalt binder, filler and fine aggregate fraction) resulting in lower fracture energy. For a finer mix, however, cracks generally propagate through the aggregate, as shown in Figure 9. As a result, S4 mixes were expected to exhibit higher cracking resistance than S3 mixes.

I-FIT or Illinois SCB test

As discussed earlier, Flexibility Index (FI), based on the load-displacement curve in the I-FIT method, was used as an

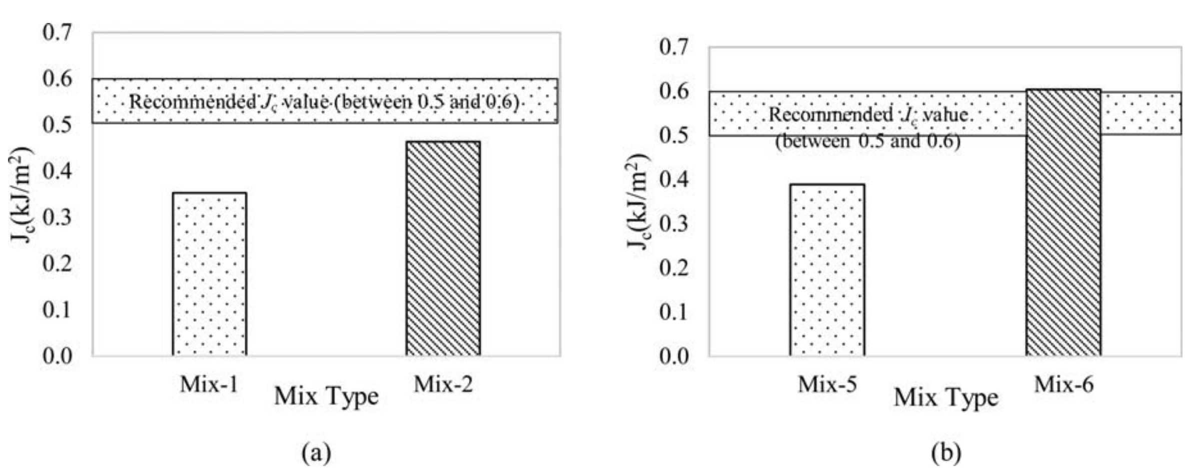

Figure 8. J_c values for (a) S3 mixes and (b) S4 mixes.

Figure 9. Cracking mechanism for (a) S3 mixes and (b) S4 mixes.

indicator of cracking resistance for asphalt mixes. Asphalt mixes with higher FI values are expected to show better cracking resistance (Ozer *et al.* 2016). Also, a higher FI value indicates a ductile material and vice versa. In this study, four I-FIT samples were tested for each mix type to obtain an average FI value. The cracking resistance of asphalt mixes using FI value was found to follow a similar trend as that of Louisiana SCB test. The foamed WMA exhibited higher cracking resistance compared to the HMA (Figure 10). The average FI value for Mix-1 was found to be 2.4 with a standard deviation of 0.6. The corresponding average FI value for Mix-2 was 4.3 with a standard deviation of 0.7. Also, the average FI values for Mix-5 and Mix-6 were 3.8 and 9.2 with standard deviations of 0.8 and 1.0, respectively. Therefore, Mix-2 and Mix-6 exhibited higher FI values compared to Mix-1 and Mix-5, respectively (Figure 10). A lower degree of aging in WMA is expected to increase their cracking resistance (Hurley and Prowell 2006, Alhasan *et al.* 2014, Malladi 2015).

The recommended minimum FI value to ensure cracking resistance varies from state to state (Ozer *et al.* 2016). According to Ozer *et al.* (2016), asphalt mixes with FI values greater than 6.7 may be classified as 'best performing', while mixes with FI values less than 2.0 may be considered 'poor performing'. Mixes with FI values between these two ranges are expected to exhibit 'intermediate performance'. Based on these criteria, Mix-6 can be classified as 'best performing', while the other three mixes are expected to exhibit 'intermediate performance' with respect to cracking resistance.

Similar to Louisiana SCB test, S4 mixes were found to exhibit higher FI values compared to the S3 mixes. This may be attributed to increased brittleness of asphalt mixes with incorporation of high amount of RAP in S3 mixes (25%) compared to S4 mixes (5%) (Shu *et al.* 2008, Guo *et al.* 2014, Lu and Saleh 2016). Also, a coarser aggregate gradation for S3 mixes is believed to be responsible for the propagation of cracking within the mastic, as shown in Figure 9.

Comparison between Louisiana SCB and I-FIT

It was observed from Figure 11 that the cracks were more prominent in the case of I-FIT than that of Louisiana SCB test method due to rapid loading and smaller notch depth (Li and Marasteanu 2010, Khan 2016, Aliha *et al.* 2018). Therefore, the Fracture Process Zone (FPZ) developed in case of I-FIT is expected to be larger than Louisiana SCB (Li and Marasteanu 2010, Khan 2016, Aliha *et al.* 2018). Several factors namely, air voids, materials heterogenicity, aggregates type, loading rate, test temperature and prefabricated notch in the specimen are believed to control the extension of FPZ (Li and Marasteanu 2010). In this study, same testing temperature (25°C) was maintained for both test methods. However, a higher loading rate (50 mm/min) was used for the I-FIT test than the Louisiana SCB test method (0.5 mm/min). Also, a smaller prefabricated notch depth (15 mm) was proposed for I-FIT test compared to Louisiana SCB (25.4, 31.8, and 38.0 mm). It was reported by Li and Marasteanu (2010) that the length of FPZ increases with a decrease in notch depth. Therefore, the length of FPZ for I-FIT tested specimen is expected to be greater than Louisiana tested specimens, as shown in Figure 11. Furthermore, due to stress concentrations, the crack in the notched specimen does not initiate at the center of the cut but close to one of the corners of the notch for

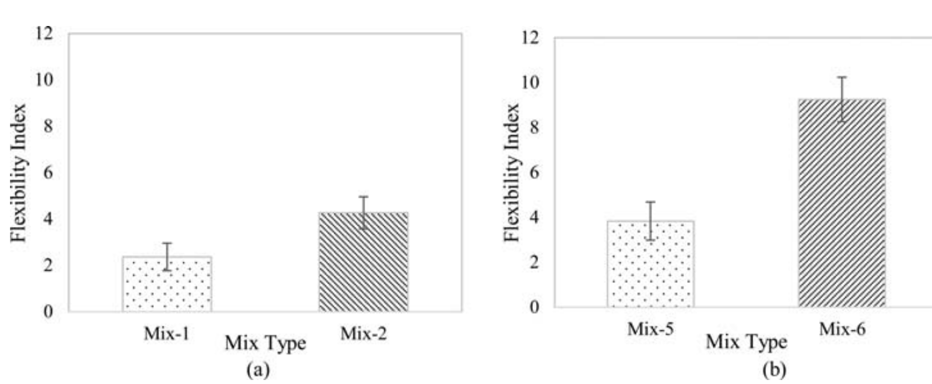

Figure 10. Flexibility index for (a) S3 mixes and (b) S4 mixes.

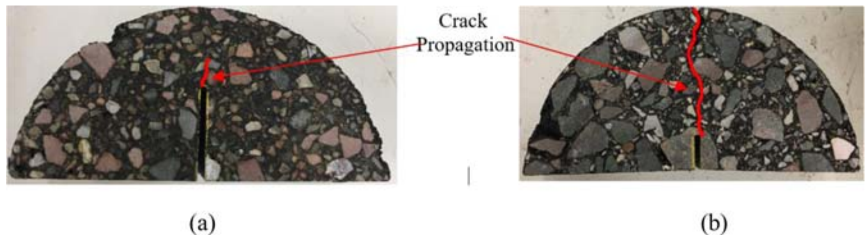

Figure 11. Flexibility SCB tested specimens (a) Louisiana SCB (LOADING RATE 0.5 mm/min) and (b) I-FIT (loading rate 50 mm/min).

both methods (Figure 11). The specimen becomes asymmetric after the initiation of crack.

Figure 12 shows the load-displacement diagrams for typical Louisiana SCB and I-FIT specimens. A higher peak load and stiffer pre-slope were observed for I-FIT samples compared to the Louisiana SCB samples for all mixes. On the contrary, the load-displacement curves for the Louisiana SCB tested samples were found to be flatter indicating a more ductile behaviour than the I-FIT samples in all cases. This is primarily caused by a higher loading rate for the I-FIT method than that of the Louisiana SCB method. According to Khan (2016), the elastic component of a viscoelastic material becomes greater with an increase in loading rate. Also, the area under the load-displacement curve for the I-FIT method was larger than the corresponding area in the Louisiana SCB method for all notch depths. Based on these observations a higher toughness can be expected for the I-FIT samples compared to the Louisiana SCB samples (Kim *et al.* 2012, Khan 2016, Saeidi and Aghayan 2016).

Abrasion loss test or Cantabro test

A higher Mass Loss (ML) in the Cantabro test indicates a lower cracking resistance and vice versa (NCAT 2017). Figure 13(a) shows the percent ML for Mix-1 and Mix-2. For each mix type three specimens were tested to check the reproducibility of test results. The average ML for Mix-1 and Mix-2 were found to be 29% and 17%, respectively. The standard deviations for Mix-1 and Mix-2 were found to be 2.6% and 3.9%, respectively. Therefore, Mix-2 exhibited a higher cracking resistance than Mix-1. A lower degree of aging for WMA is expected to result in an increase in cracking resistance (Hurley and Prowell 2006, Alhasan *et al.* 2014, Malladi 2015). However, Jones *et al.* (2010) and Bonaquist (2011) reported similar cracking resistance for both HMA and WMA with the same aggregate and binder PG. These findings are different from those of the present study for S3 mixes. A combination of factors such as ambient moisture in aggregate, type of aggregate, amount of RAP, sources of RAP, age of RAP, type and amount of virgin binder can be responsible for this difference. Also, it was observed that the

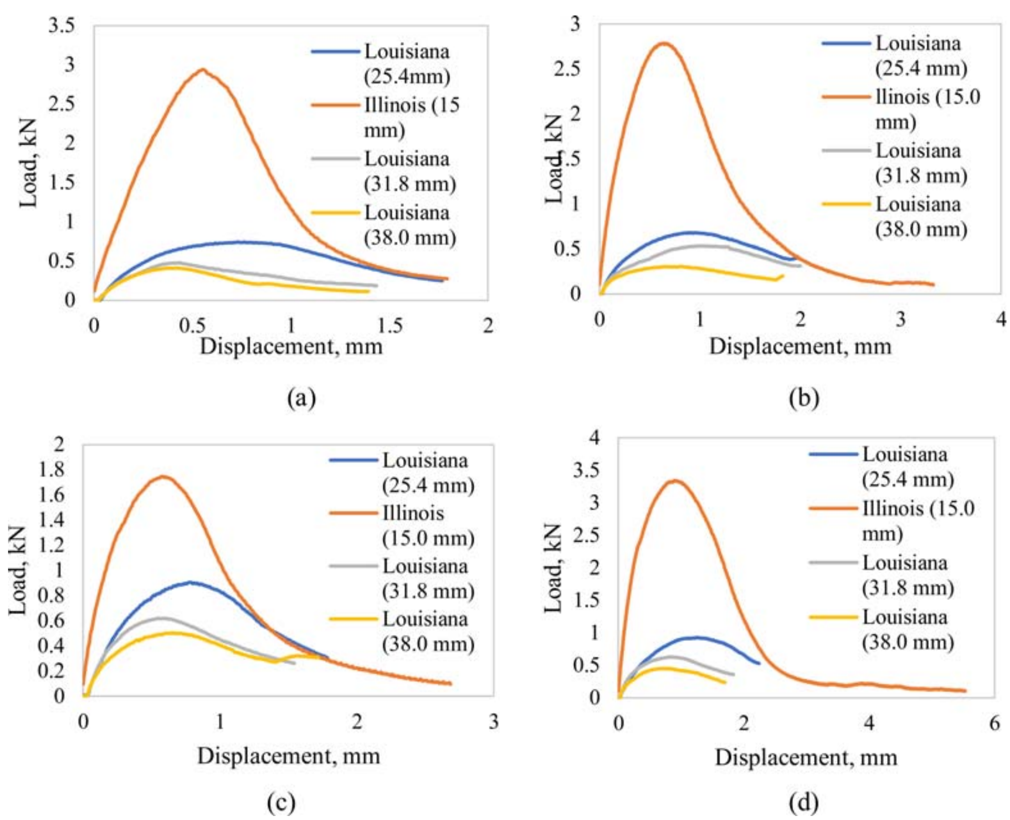

Figure 12 .Load-displacement diagram for Louisiana SCB and I-FIT tested specimens (a) Mix-1 (b) Mix-2 (c) Mix-5 (d) Mix-6.

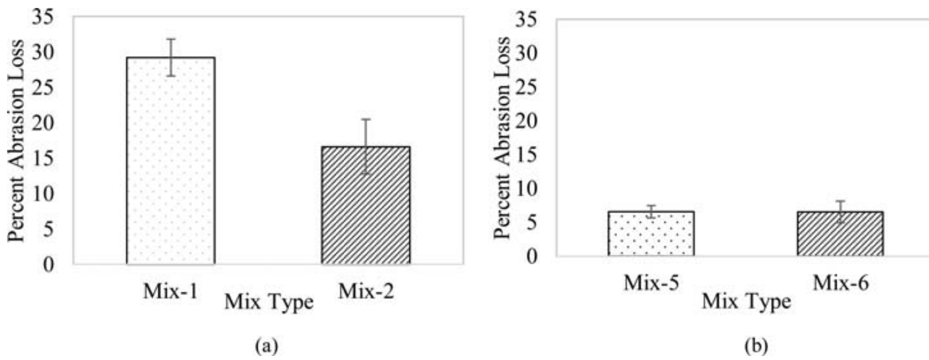

Figure 13 .Percent abrasion loss for (a) S3 mixes and (b) S4 mixes.

Cantabro test results follow a similar trend as the Louisiana SCB and I-FIT test results for S3 mixes. Therefore, this test method may be considered as an alternative method for screening coarser asphalt mixes for cracking during the mix design stage.

The same average ML (7%) for both Mix-5 and Mix-6 samples was observed from Cantabro tests (Figure 13(b)). The standard deviations for Mix-5 and Mix-6 were found to be 0.9% and 1.6%, respectively. Based on these results, similar cracking resistance is expected for both S4 mixes. However, Mix-6 was found to exhibit a higher cracking resistance than Mix-5 in both Louisiana SCB and I-FIT tests. The Cantabro test is an empirical test with no clear mechanistic basis for simulation of fatigue cracking. This test method was originally developed to check the abrasion loss of asphalt mixes (AASHTO 2016a). The adhesive bonding between aggregates and binder under impact load is mainly evaluated in this test method (Du and Li 2011). In case of S4 (finer) mixes a higher binder content (4.9%) was used compared to S3 (coarser) mixes (4.5%), which is believed to improve the adhesion between aggregates and binder. Therefore, both S4 mixes were found to exhibit similar percent ML (7%). However, the effect of abrasion is more pronounced in case of S3 mixes due to a lower amount of binding material. Therefore, Mix-1 was found to exhibit higher ML compared to Mix-2. Also, both Louisiana SCB and I-FIT tests are mechanistic-based methods for evaluating cracking resistance. Disagreement with the Louisiana SCB and I-FIT test results indicates the limitation of Cantabro test in screening of fine mixes (S4 here) for cracking. A relatively higher ML for S3 mixes compared to S4 mixes can be attributed to increased RAP content (Shu *et al.* 2008, Guo *et al.* 2014, Lu and Saleh 2016, Saeidi and Aghayan 2016). Both S3 mixes did not satisfy the NCAT abrasion ML requirement of 20%, whereas S4 mixes satisfied the requirement (NCAT 2017).

Ranking of asphalt mixes based on cracking resistance

Table 4 presents the ranking of all four mixes (Mix-1, Mix-2, Mix-5, and Mix-6) based on their resistance to fatigue cracking. The rating was conducted on a scale of 1 to 4, where 1 represents the best performing and 4 represents the worst performing asphalt mix with respect to fatigue cracking resistance. It was found that the Louisiana SCB, I-FIT and dynamic modulus values at 10^{-4} Hz reduced frequency ranked the fatigue cracking resistance of asphalt mixes in similar orders.

Table 4. Ranking of asphalt mixes based on fatigue cracking performance.

Mix type	Louisiana SCB	I-FIT	Cantabro test	Dynamic modulus
Mix-1	4	4	4	4
Mix-2	2	2	3	2
Mix-5	3	3	1	3
Mix-6	1	1	1	1

However, Cantabro test could not differentiate the fatigue cracking resistance of Mix-5 and Mix-6. Therefore, although the Cantabro test is easier to conduct, it may not be able to characterise the fatigue resistance of asphalt mixes as consistently as the Louisiana SCB and I-FIT tests.

Based on the Louisiana SCB and I-FIT test results, Mix-6 was found to exhibit the highest resistance to fatigue cracking followed by Mix-2, Mix-5, and Mix-1. From these results it can be concluded that a foamed WMA with fine aggregate gradation and low RAP content is expected to perform well in fatigue. The cracking resistance may reduce with coarser aggregate gradation and increased RAP content.

Conclusions

The mix design volumetrics and fatigue cracking potential of foamed WMA were evaluated and compared with control HMA containing the same amount of RAP. The mix design volumetrics were checked based on the AASHTO R 35 method. On the other hand, the dynamic modulus, Louisiana SCB, I-FIT and Abrasion Loss tests were conducted to evaluate the cracking resistance of asphalt mixes. Based on the results found in this study, the following conclusions can be drawn.

(i) It was found that both fine and coarse foamed WMA exhibited similar percent air voids as HMA when using the current practice of mixing (135°C) and compaction (127°C) temperatures of foamed WMA. The corresponding *p*-values for the fine and coarse mixes were 0.98 and 0.58, respectively, indicating insignificant differences in air voids for both foamed WMA and HMA, at the 95% confidence level. The reduction in mixing and compaction temperatures for foamed WMA compared to HMA did not cause any problem related to coating and compaction up to certain lower temperatures.

(ii) While incorporating RAP, compaction temperature greater than the high-temperature PG of RAP was found to exhibit similar volumetric properties for WMA compared to HMA. However, in this study, the mixing and compaction temperatures of the mix, along with the high-temperature PG of RAP, was found to govern the volumetric properties of the foamed WMA containing RAP. Significant differences in the percent air voids between foamed WMA and HMA mixes were observed while mixing and compacting were performed at temperatures lower than the practice temperatures but higher than the high-temperature PG of RAP.

(iii) The Louisiana SCB and I-FIT tests were found to follow a similar trend in screening asphalt mixes for cracking resistance. A higher J_c value and FI index were observed for foamed WMA than HMA indicating higher cracking resistance. A higher fatigue resistance of foamed WMA was expected due to a lower stiffness found in the dynamic modulus testing.

(iv) The percent abrasion ML in the Cantabro test was found to provide inconsistent results compared to the Louisiana SCB and I-FIT tests for fine mixes. Although this test is easier to conduct than SCB tests, it may not properly screen mixes for their fatigue resistance. Lack of a strong mechanistic basis could be attributed to such inconsistencies. SCB test methods (both Louisiana and I-FIT) provided consistent results indicating that these test methods can be used for screening of both WMA and HMA for fatigue cracking resistance of asphalt mixes.

(v) Incorporation of RAP was found to increase the stiffness of asphalt mixes, which resulted in lower fatigue resistance. Also, the finer mixes showed higher cracking resistance than coarser mixes due to differences in crack propagation mechanisms. For finer mixes crack was found to propagate through the aggregates, whereas crack mostly propagated through the mastic for coarser mixes.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Southern Plains Transportation Center (SPTC).

ORCID

Mohammad Ashiqur Rahman http://orcid.org/0000-0001-7855-5346
Syed Ashik Ali http://orcid.org/0000-0001-8552-3377
Rouzbeh Ghabchi http://orcid.org/0000-0002-3827-6315
Sagar Ghos http://orcid.org/0000-0002-8768-2854

References

AASHTO R 30, 2002. *Standard practice for mixture conditioning of hot mix asphalt (HMA)*. Washington, DC: The American Association of State Highway.

AASHTO R 35, 2013. *Standard practice for superpave volumetric design for asphalt mixtures*. Washington, DC: The American Association of State Highway.

AASHTO T 166, 2010. *Standard method of test for bulk specific gravity of compacted hot-mix asphalt using saturated surface-dry specimens*. Washington, DC: The American Association of State Highway.

AASHTO T 209, 2012. *Theoretical maximum specific gravity (Gmm) and density of hot mix asphalt (HMA)*. Washington, DC: The American Association of State Highway.

AASHTO T 315, 2018. *Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)*. Washington, DC: The American Association of State Highway.

AASHTO T 378, 2017. *Standard method of test for determining the dynamic modulus and flow number for asphalt mixtures using the asphalt mixture performance tester (AMPT)*. Washington, DC: The American Association of State Highway.

AASHTO TP 108, 2016a. *Standard practice for abrasion loss of asphalt mixture specimens*. Washington, DC: The American Association of State Highway.

AASHTO TP 124, 2016b. *Determining the fracture potential of asphalt mixtures using semicircular bend geometry (SCB) at intermediate temperature*. Washington, DC: The American Association of State Highway.

Abuawad, I.M., Al-Qadi, I.L., and Trepanier, J.S, 2015. Mitigation of moisture damage in asphalt concrete: testing techniques and additives/modifiers effectiveness. *Construction and Building Materials*, 84, 437–443.

Al-Qadi, I.L., *et al.*, 2015. *Testing protocols to ensure performance of high asphalt binder replacement mixes using rap and ras*, 0197-9191.

Alhasan, A.A., *et al.*, 2014. Low-temperature characterization of foamed warm-mix asphalt produced by water injection. *Transportation Research Record*, 2445 (1), 1–11.

Ali, A., *et al.*, 2013. Effect of temperature reduction, foaming water content, and aggregate moisture content on performance of foamed warm mix asphalt. *Construction and Building Materials*, 48, 1058–1066.

Aliha, M., *et al.*, 2018. The effect of loading rate on fracture energy of asphalt mixture at intermediate temperatures and under different loading modes. *Frattura ed Integrità Strutturale*, 12 (43), 113–132.

Baek, J, 2010. *Modeling reflective cracking development in hot-mix asphalt overlays and quantification of control techniques*. University of Illinois at Urbana-Champaign, IL, USA.

Barman, M., *et al.*, 2018. An alternative analysis of indirect tensile test results for evaluating fatigue characteristics of asphalt mixes. *Construction and Building Materials*, 166, 204–213.

Bonaquist, R.F, 2011. *Mix design practices for warm mix asphalt*. Transportation Research Board, Washington D.C., USA.

Chehab, G.R., O'quinn, E., and Richard Kim, Y, 2000. Specimen geometry study for direct tension test based on mechanical tests and air void variation in asphalt concrete specimens compacted by superpave gyratory compactor. *Transportation Research Record*, 1723 (1), 125–132.

Colombier, G, 2004. Cracking in pavements: Nature and origin of cracks. *Prevention of reflective cracking in pavements*. CRC Press, 14–29.

Copeland, A., *et al.*, 2010. Field evaluation of high reclaimed asphalt pavement–warm-mix asphalt project in Florida: case study. *Transportation Research Record*, 2179 (1), 93–101.

Dong, F., *et al.*, 2017. Comparison of high temperature performance and microstructure for foamed wma and hma with rap binder. *Construction and Building Materials*, 134, 594–601.

Du, S., and Li, S, 2011. The raveling characteristic of porous asphalt mixture. *Icte 2011*, 1880–1885.

Ghabchi, R, 2014. Laboratory characterization of recycled and warm mix asphalt for enhanced pavement applications.

Ghabchi, R., *et al.*, 2016. Comparison of laboratory performance of asphalt mixes containing different proportions of Ras and Rap. *Construction and Building Materials*, 124, 343–351.

Goh, S.W., and You, Z, 2011. Mechanical properties of porous asphalt pavement materials with warm mix asphalt and rap. *Journal of Transportation Engineering*, 138 (1), 90–97.

Guo, N., *et al.*, 2014. Laboratory performance of warm mix asphalt containing recycled asphalt mixtures. *Construction and Building Materials*, 64, 141–149.

Huang, B., *et al.*, 2004. Fatigue crack characteristics of HMA mixtures containing raped. *Proceeding 5th Int. Conf. on Cracking in Pavements, RILEM*, 631–638.

Hurley, G.C., and Prowell, B.D, 2006. Evaluation of potential processes for use in warm mix asphalt. *Journal of the Association of Asphalt Paving Technologists*, 75, 41–90.

Jenkins, K.J, 2000. *Mix design considerations for cold and half-warm bituminous mixes with emphasis of foamed bitumen*. Stellenbosch: Stellenbosch University.

Jones, W, 2004. Warm mix asphalt-a state-of-the-art review. *Australian Asphalt Pavement Association Advisory Note*, 17.

Jones, C., 2008. Summit on increasing rap use in pavements sate's perspectived. *North Carolina Department of Transportation, presented at Morerap conference at Auburn, AL, USA*.

Jones, D., *et al.*, 2010. *Warm-mix asphalt study: laboratory test results for akzonobel redisettm wmx*. University of California, Pavement Research Center, Davis, CA.

Khan, A., 2016. *Displacement rate and temperature effect on asphalt concrete cracking potential*.

Kheradmand, B., *et al.*, 2014. An overview of the emerging warm mix asphalt technology. *International Journal of Pavement Engineering*, 15 (1), 79–94.

Kim, M., Mohammad, L.N., and Elseifi, M.A, 2012. Characterization of fracture properties of asphalt mixtures as measured by semicircular bend test and indirect tension test. *Transportation Research Record*, 2296 (1), 115–124.

Li, X., and Marasteanu, M, 2010. The fracture process zone in asphalt mixture at low temperature. *Engineering Fracture Mechanics*, 77 (7), 1175–1190.

Lu, X.D., and Saleh, M, 2016. Evaluation of warm mix asphalt performance incorporating high rap content. *Canadian Journal of Civil Engineering*, 43 (4), 343–350.

Malladi, H., 2015. Investigation of warm mix asphalt concrete mixtures with recycled asphalt pavement material.

Mcdaniel, R.S., *et al.*, 2000. Recommended use of reclaimed asphalt pavement in the superpave mix design method. *NCHRP Web document*, 30.

Napa, 2015. *Simple durability tests on mixes from the FHWA ALF experiment*. National Asphalt Pavement Association, Lanham, MD, USA.

Ncat, 2017. *Twins at birth differed as they aged, by Don Watson*. National Center for Asphalt Technology, Auburn, AL, USA.

Odot, 2013. Oklahoma department of transportation special provision for reclaimed asphalt pavement and shingles, 2013. Available from: http://www.oorg/c_manuals/specprov2009/oe_sp_2009-708-21.pdf [Accessed 30 August 2018].

Ozer, H., *et al.*, 2016. Development of the fracture-based flexibility index for asphalt concrete cracking potential using modified semi-circle bending test parameters. *Construction and Building Materials*, 115, 390–401.

Prowell, B.D., Hurley, G.C., and Crews, E, 2007. Field performance of warm-mix asphalt at national center for asphalt technology test track. *Transportation Research Record*, 1998 (1), 96–102.

Roberts, F.L., *et al.*, 1991. Hot mix asphalt materials, mixture design and construction.

Rubio, M.C., *et al.*, 2012. Warm mix asphalt: An overview. *Journal of Cleaner Production*, 24, 76–84.

Saeidi, H., and Aghayan, I, 2016. Investigating the effects of aging and loading rate on low-temperature cracking resistance of core-based asphalt samples using semi-circular bending test. *Construction and Building Materials*, 126, 682–690.

Shu, X., Huang, B., and Vukosavljevic, D, 2008. Laboratory evaluation of fatigue characteristics of recycled asphalt mixture. *Construction and Building Materials*, 22 (7), 1323–1330.

Singh, D., 2011. *A laboratory investigation and modeling of dynamic modulus of asphalt mixes for pavement applications*.

Zhao, S., *et al.*, 2012. Laboratory performance evaluation of warm-mix asphalt containing high percentages of reclaimed asphalt pavement. *Transportation Research Record*, 2294 (1), 98–105.

Zhao, S., *et al.*, 2013. Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement. *Construction and Building Materials*, 44, 92–100.