https://dx.doi.org/10.1016/j.conbuildmat.2018.04.218

Workability and Mechanical Property Characterization of Asphalt Rubber Mixtures Modified with Various Warm Mix Asphalt Additives

Huayang Yu[a], Zhen Leng[b*], Zejiao Dong[c], Zhifei Tan[b], Feng Guo[b], Jinhai Yan[b]

[a]School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, China.

[b]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.

[c]School of Transportation Science and Technology, Harbin Institute of Technology, Harbin, China.

*Corresponding author: Tel: 852-2766-6007; Fax: 852-2334-6389; Email: zhen.leng@polyu.edu.hk

ABSTRACT

Warm mix asphalt (WMA) technology offers a promising solution to address the workability concern of asphalt rubber (AR) mixture. Warm asphalt rubber (WAR), the combination of AR and WMA, is expected to be a sustainable paving technology that integrates energy conservation, waste management, noise reduction, and performance optimization. This study aims to characterize and compare the engineering properties of WAR mixture prepared with various WMA additives. To achieve this goal, WAR mixtures were prepared with 40-mesh crumb rubber and five different WMA additives, including Evotherm-DAT, Evotherm-3G, Sasobit, 56# paraffin wax and Aspha-min. Comprehensive laboratory tests were conducted to characterize their workabilities and engineering properties, including moisture susceptibility, stiffness modulus, dynamic modulus, and rutting and fatigue resistance. According to the experimental results, by using WMA additives, a 16 ^{o}C reduction in construction temperature can be achieved without significantly deteriorating the mixtures' compactability. WMA additives influenced both the stiffness modulus and dynamic modulus of AR mixture. All WMA additives compromised the rutting resistance of AR mixture except for Sasobit, and the influence of WMA additives on the moisture susceptibility was insignificant. In terms of the fatigue performance, only Evotherm-DAT provided a positive effect. Finally, effects of WMA additives on AR binders and mixtures' properties followed the similar tendency, except for the fatigue performance.

Key Words*:* Warm mix additives, asphalt rubber, mechanical properties, workability

1 Introduction

Asphalt rubber (AR) is a modified asphalt binder, which is composed of raw asphalt binder and no less than 15% of crumb rubber modifier (CRM) by total binder weight [1]. The high consumption of crumb rubber helps address the environmental concern on the disposal of waste vehicle tires [2]. Moreover, AR pavement is environmentally beneficial due to its tire-road noise reduction effect [3]. It was also reported that mixtures with AR binder provide superior rutting resistance and fatigue cracking resistance [4, 5]. Despite the attractive merits of AR, there is one inherent problem which limits its wide application. Incorporation of crumb rubber significantly increases the asphalt binder viscosity, which in turn increases the required blending and compacting temperatures, resulting more energy consumption and emissions during pavement construction [6]. One potential solution is to use warm mix asphalt (WMA) technology to address the workability concern, making AR more sustainable [7]. If the production temperature for AR mixtures can be reduced by using WMA technologies without compromising their engineering performance, their overall benefits to both environment and society will be significant.

The engineering performance and working mechanism of both AR and WMA have been well studied [8-10]. The interaction of CRM and base asphalt is reported to be a component exchange process [11]. At elevated temperature, CRM particles absorb asphalt fractions during swelling and release rubber components during depolymerization and devulcanization, which makes the modified binder stiffer and more elastic [12]. Compared to base asphalt, AR binder exerts improved performance in rutting, fatigue and low temperature cracking [13, 14]. When used together, WMA additives are expected to enhance mixtures' wrorkability while CRM is expected to provide superior mechanical properties. Due to their different physical natures and working mechanisms, WMA technologies may have different effects on binder properties and mixture performance [15].

When WMA and AR are used together, WMA is expected to influence both the component interaction and engineering performance of AR. Recent studies indicated that chemical and organic additives promote the dissolution of CRM in base asphalt [11], in addition, during the mixing process, CRM particles not only absorb light fractions of raw asphalt, but also certain amount of WMA additives [16]. In terms of the engineering performance, previous studies have proven that most WMA technologies can effectively reduce the viscosity of AR binder at elevated temperatures, resulting in enhanced mixture workability [17-19]. However, the effects of WMA technologies on mixtures' mechanical performance vary. Several studies have reported that the moisture damage resistance of WAR mixture is slightly poorer than that of hot AR mixture as less moisture from aggregate evaporates at lower production temperature [20, 21]. This finding was also supported by a study on surface free energy, showing that AR with Rediset, Sasobit and Advera displayed poorer moisture resistance than hot AR [22]. However, Oliveira et al. hold the opposite view because they observed that surfactant additives enhance water sensitivity as the bond between aggregates and binder can be improved by surfactant [4]. Jones et al. concluded that the warm-mix technology by itself is unlikely to influence moisture sensitivity; however, problems are more likely caused by aggregate condition and construction quality [23]. In terms of fatigue performance, Xiao et al. reported that among Sasobit, Evotherm and Aspha-min, only Aspha-min led to poorer fatigue cracking resistance [24]. With respect to rutting resistance, WAR mixtures with Sasobit and surfactant-type additives were reported to provide better performance than hot AR [4, 25]. Moreover, the effects of both foaming additives and foaming process on rutting resistance of rubberized asphalt mixtures were found insignificant [21].

Although the performance of WAR mixtures has been investigated by various studies, comprehensive studies covering all three types of WMA technologies and WAR mixtures' engineering properties in full spectrum, are still very limited. To this end, this study aims to evaluate the overall engineering performance of WAR mixtures by characterizing the mixtures' workability, modulus, moisture susceptibility, rutting resistance and fatigue resistance. This study is expected to provide extensive information for selecting appropriate type of WMA technology for field application of WAR.

2 Experimental Program

2.1 Materials and Sample Preparation

The raw bitumen (with penetration grade of 60/70) used in this study was supplied by Anderson Asphalt Ltd., a local asphalt company in Hong Kong. AR binder was prepared by high shearing mixing of CRM and raw asphalt for one hour. The mixing temperature was 176 °C and the mixing rate was set as 4000rpm, following the previous AR studies [13, 26, 27].

In total, five representative WMA additives were selected, including: two chemical additives (Evotherm-DAT and Evotherm-3G), two organic additives (Sasobit and 56# paraffin wax), and one foaming additive (Aspha-min). Evotherm-DAT and Evotherm-3G are chemical additives, which act as surfactants between asphalt binder and aggregates. Sasobit (commercial WMA additive produced by the Fisher-Tropsch process) and 56# paraffin wax (conventional wax) are organic additives, which act as flow improvers for viscous binder due to their low viscosities after melting. The purpose of using 56#

paraffin wax was to evaluate whether the negative influence of the conventional wax on low-temperature properties can be compensated by CRM when they are used together [13, 27]. Aspha-min is a special type of synthetic zeolite, which contains approximately 19-21wt% of water which can be released during the asphalt blending process. Table 1 presents the basic information of the five WMA additives used in this study.

The WAR binders were prepared by blending WMA additives into hot binder right after the preparation of AR. The blending process was conducted at 160 ^{o}C, with a shearing speed of 800rpm, and lasted for 10 minutes. Based on our previous experience and studies, the WMA additives can be completely dissolved in AR binder. A reaction procedure of 1-hour storing was conducted for AR and WAR binders. The prepared WAR binders were labelled as ARE, ARE3G, ARS, ARW and ARMIN, representing those using Evotherm-DAT, Evotherm-3G, Sasobit, 56$^{\#}$ paraffin wax and Aspha-min, respectively. The rheological properties of Pen 60/70 virgin binder, and the prepared AR and WAR binders are shown in Table 2.

The mixture design for the 10mm aggregate size stone mastic asphalt (SMA10, Table 3), which is commonly used in Hong Kong, was selected for mixture preparation. The optimum asphalt contents for AR and WAR binders were 6.6% as designed by the Marshall method. Corresponding to the binder samples, six groups of mixture samples were prepared, including AR, ARE, ARE3G, ARS, ARW and ARMIN mixtures. The target air void is 4%. Specimens prepared by a Superpave gyratory compactor (SGC) were used for the indirect tensile strength (ITS) test, indirect tensile stiffness modulus (ITSM) test, indirect tensile fatigue test (ITFT) and dynamic modulus test. Rutting slabs prepared by a rolling compactor were used for loaded wheel track (LWT) test. The mixing temperatures of hot and warm AR mixtures were 176 °C and 160 °C, respectively. The compaction temperatures were approximately 15 °C lower than the corresponding mixing temperatures. Three replicates were prepared for each performance test.

2.2 Testing Program

The engineering properties of the WAR mixtures prepared with five WAR binders (ARE, ARE3G, ARS, ARW and ARMIN) were characterized by laboratory tests. To evaluate the effects of the warm mix additives on workability, trial compactions of WAR mixtures were performed at a temperature 16 °C lower using both Marshall compaction and SGC methods. The warm mix effect was evaluated by the compactability of the mixtures. The mechanical properties of the WAR mixtures, including stiffness, rutting resistance, fatigue cracking resistance, and moisture sensitivity were also measured. The stiffness of the mixtures was determined using the ITSM test. The resistance to permanent deformation was measured by the LWT test. The fatigue resistance was examined using the ITFT test. The moisture sensitivity was determined by conducting the ITS test before and after freeze-thaw cycling. In addition, the simple performance test was conducted to evaluate the linear viscoelastic properties of the WAR mixtures. The experimental framework of the mixture mechanical characterization is shown in Figure 1. Figure 2 provides a few representative images during the testing process. Detailed information on the testing conditions, sample sizes and relevant standards are summarized in Table 4.

3 Results and Discussion

3.1 Workability

In this study, the selected mixing temperature of the AR mixture was 176 °C, same as the production temperature of the AR binder. All WAR mixtures were mixed at 160 °C, which is 16 °C lower than the mixing temperature of the AR mixture, to assess their workabilities. The compacting temperature for each sample is 15 °C lower than its corresponding mixing temperature.

Similar to the methods used in one of the previous studies [27], the compactabilities of the WAR mixtures were measured based on the air void contents of the Marshall specimens (75 hammer blows on each side) and the numbers of gyrations of the SGC specimens to achieve the same specimen height (40 mm). The weights of aggregate, base asphalt and CRM were kept same for specimens. Therefore, a low air void content of the Marshall sample or a smaller gyration number of the SGC specimen indicates a better compatability of the mixture.

Figure 3a shows the air void contents of the Marshall specimens. All WAR specimens had similar air void contents (ranging from 4.0% to 4.5%) compared to AR specimens (4.1%), demonstrating that all WMA additives could reduce the mixing temperature by at least 16 °C. Among the WARs, mixtures with Evotherm-DAT and Aspha-min showed smaller air void contents, indicating their better workability. The compactability of ARS mixture at a lower temperature is very close to that of the hot AR mixture. The air void contents of the ARE3G and ARW mixtures were slightly larger than that of hot AR mixture. A possible reason is that the dosage of ARE3G is not sufficient as CRM may absorb part of the WMA additive during the mixing process [11].

Similar findings were obtained from the SGC tests (Figure 3b). The gyration numbers of most WAR mixtures were similar to that of the hot AR mixture to achieve the same specimen height. The only exception is the ARE3G mix, which needed 52 more gyrations compared with the hot AR mix. Both evaluation methods demonstrated that among different WAR mixtures, ARE provides the best workability followed by ARS, ARMIN, ARW and ARE3G. For those with non-foaming WMA additives, the compactiabilities of their corresponding mixtures were generally consistent with their rotational viscosities (Table 2).

3.2 Moisture Susceptibility

Moisture damage is a major concern for WMA mixtures, as the lower mixing temperature may result in insufficient evaporation of moisture in aggregates. The moisture susceptibilities of the WAR mixtures were evaluated by comparing the ITS values before and after freeze-thaw conditioning, according to ASTM D4867. The freeze-thaw process started with a vacuum saturation of the test sample, followed by a freeze (-18 ^{o}C, 16h) and warm conditioning (60 ^{o}C, 24h). Prior to the ITS test, the mixture specimen was placed in a water bath (25 ^{o}C) for no less than 2 hours. Three parallel samples were prepared and tested, and the results of each mixture are presented in Figure 4 and Table 5. In Table 5, M_x is the mean of ITS test values, and Vx is the coefficient of variation of the test results [28].

Under dry condition, ARS had the highest stiffness and ARE had the lowest. The three other WAR mixtures, namely ARE3G, ARW and ARMIN, exhibited slightly lower ITS compared with the AR mixture. Moreover, ARS exhibited higher ITS value than AR after the freeze-thaw cycle, and the ITS ranking of the six types of mixtures remained unchanged before and after conditioning. The resistance of asphalt mixture to the detrimental damage caused by moisture is usually expressed as tensile strength ratio (TSR), which is defined as the tensile strength ratio of dry and soaked specimens after a freeze-thaw cycle [29]. The higher the TSR value, the better moisture damage resistance of the mixture. As shown in Table 5, the TSR values of AR and WAR mixtures ranged from 78.30% to 88.40%. Most agencies recommended 70% as the threshold TSR [30, 31]. Therefore, all WAR mixtures exhibited acceptable moisture susceptibility according to their TSR values. From Table 5, it can also be seen that ARE3G had the highest TSR (88.40%) and ARE had the lowest (78.30%). The relatively poor performance of ARE may be ascribed to the high dosage of Evotherm-DAT additive, and the liquid additive may have not evaporated completely during the mixing process. Only ARE3G and ARW performed better than hot AR, whereas ARS and ARMIN displayed slightly poorer performance.

In general, the moisture damage resistances of all WAR mixtures are satisfactory. One potential reason is that for AR mixtures, despite the usage of WMA additives, their mixing temperatures (160 °C) are still relatively high and close to those of the conventional bituminous mixes.

3.3 Stiffness Modulus

In ITSM test, repeated load pulses with a peak stress value of 200 MPa, and a given rise time of 124 ms out of a 0.1 s loading time is applied to the vertical diameter of the cylindrical specimen. After each loading, the specimen is left to rest for 0.9 s. Figure 5 shows the ITSM test results. It can be seen that ARS mix showed the highest stiffness modulus consecutively followed by AR, ARMIN, ARE3G, ARW and ARE mixes. With the same aggregate and mixture gradation, the stiffness modulus of the mixture is mainly influenced by the rheology of asphalt binder. Sasobit enhanced the binder stiffness and thus improved the stiffness of the mixture. Other WMA additives showed negative effect on ITSM value. Among all WMA additives, Evotherm-DAT caused the most significant reduction of the mixture's modulus.

3.4 Dynamic Modulus

Asphalt mixture behaves as a linear viscoelastic material at low strain level, its stress-strain relationship under a continuous sinusoidal loading is defined as complex modulus, E^* [32]. Previous research has found that the dynamic modulus of an asphalt mixture at high service temperature (54.4 ^oC) has excellent correlation with its field rutting resistance, while its intermediate-temperature dynamic modulus had fairly good correlation with its fatigue cracking resistance [33]. In this study, the linear viscoelastic properties of the AR and WAR mixes were characterized by the dynamic modulus tests. The tests were conducted at the following three temperatures: 4, 20, and 40 °C. At each temperature, the tests were performed at the following three frequencies: 10, 1 and 0.1 Hz. At any specific temperature and loading frequency, the dynamic modulus, E^*, and phase angle, δ, were calculated by the following equations [34]:

$$|E^*|= \sigma_0/\varepsilon_0$$

$$\delta= (t_i / t_p) *360$$

where: σ_o = peak dynamic stress amplitude (psi),

ε_o = peak recoverable strain (in/in),

t_i = time lag between a cycle of stress and strain (sec),

t_p = time for a stress cycle (sec).

As expected, the dynamic modulus values increased with increasing frequency at each given temperature [32, 33]. The phase angle (δ) values decreased at low (4 °C) and intermediate (20 °C) temperatures with the increase of frequencies, whereas the opposite trend was observed at high temperature (40 °C).

Figure 6 presents the complex modulus master curves of AR and WAR mixtures with a reference temperature of 20 °C, and Figure 7 presents the modulus information at each testing temperature (4, 20 and 40 °C). Based on the time-temperature superposition principle, the dynamic modulus at different temperatures were shifted horizontally along the frequency axis to develop the master curve at the reference temperature. Figure 6a shows the results of all test samples, and Figures 6b-e compare the master curves of AR and each WAR mixture. According to the superposition principle, a high frequency is equivalent to a low temperature and vice versa. ARE and ARE3G showed lower modulus than AR at all frequencies, implying their worse rutting resistance but better low temperature performance. The master curves of ARS and AR nearly coincide, indicating their similar performances. ARMIN and ARW performed worse at both high and low temperatures compared with AR. Moreover, ARW showed the poorest low-temperature performance, which is possibly due to the high temperature susceptibility of the conventional wax.

3.5 Rutting Resistance

The high temperature performance of AR and WAR were characterized by the LWT test according to BS 598-Part110. Two parameters were used as performance indexes, i.e., rutting depth (the measured deformation of sample surface relative to the original surface) and rutting rate (the rate of rutting development at the final 15 minutes). Figure 8 and Table 6 present the rutting performance test results of AR and WAR mixtures. The average rutting depth after 45 minutes of cyclic loading was 1.69 mm for the AR mixture, and the rutting rate was 1.03mm/h. Among various WAR mixtures, only the one with Sasobit exhibited enhanced rutting resistance. The WAR with Evotherm-DAT showed the poorest resistance to permanent deformation, which is consistent with the low $G^*/\sin\delta$ and high $J_{nr}3200$ values of the ARE binder. Besides, the rutting resistance of the ARMIN mixture was very close to the AR mixture, while those of the ARE3G and ARW mixtures were noticeably worse. In the previous local study using the same experimental equipment, for the SMA10 mixtures with a Pen 60/70 binder which have been widely used in Hong Kong, a rutting depth of 2.98mm and a rutting rate of 2.28mm/h were recorded [28]. Therefore, the rutting resistances of WAR mixtures studied in this research are considered acceptable.

3.6 Fatigue Resistance

In ITFT tests, the horizontal deformation was recorded as a function of loading cycle. The failure is indicated by 9mm vertical deformation of test specimens. All test specimens were subjected to 7 different stress levels (250 to 550kPa, with 50kPa increment), for regression analysis. This allowed the development of the fatigue relationship between the number of cycles at failure and initial tensile strain on a log-log relationship. Fatigue life (N_f) of a specimen is defined as the number of cycles to fail the testing specimen." The fatigue relationship between the initial strain and the cycles to failure can be expressed as the following equation:

$$N_f = k_1(\xi)^{k_2}$$

Where ξ is the initial strain (microstrain);

N_f is the cycles to failure;

k_1 and k_2 – materials parameters.

The microstrain ξ is the maximum tensile horizontal strain, which can be obtained by the following equation:

$$\xi = \frac{\delta \times (1 + 3\nu)}{S_m} \times 1000$$

Where δ is the maximum tensile stress applied at the center of test sample;

ν is the passion ratio (0.35 for asphalt mixes);

S_m is the stiffness modulus of test sample.

In this study, the fatigue life at 100 microstrains (N_f100) was used as fatigue performance indicator. In logarithm (base 10) scale, the fatigue law equation can be transferred to

$$logN_f = logk_1 + k_2 log\xi$$

Thus, a linear relationship between log (cycles to failure) and log (microstrain) can be developed using the ITFT test results, as depicted in Figure 9. The material parameters k_1 and k_2 were obtained through regression analysis, as shown in Table 7.

Tensile strains generated under a standard axle load at the bottom of the bituminous mixture layer of a flexible road are normally in the range between 0 and 200 microstrains. To compare the fatigue performance of different mixtures, the mean strain value (of 100 microstrains) was chosen. Table 7 also provides the "cycles at 100 micro strains" of each mixture (N_f 100) from the fatigue tests. A larger number of cycles indicates a better fatigue resistance. According to Table 7, the N_f 100 values for all AR and WAR mixtures exceeded 3.45E+05. Compared with another local study, AR and WAR mixtures studied in this research showed much better fatigue performance compared with the hot SMA mixture with Pen 60/70 binder (N_f 100=1.06E+04) [28]. Among various WAR mixture samples, only the ARE mixture performed better than the AR mixture in terms of fatigue resistance. The ARS, ARW, ARMIN and ARE3G mixtures had similar fatigue performances, and the ARS mixture had the shortest fatigue life. However, as according to the binder tests results, the ARS binder showed better fatigue resistance than the AR, ARE and ARW binders (indicated by the $G^{*}\sin\delta$ results shown in Table 2), which contradicts to the mixture fatigue performance test results. One possible reason is that the fatigue factor ($G^{*}\sin\delta$) of binder may not reflect true material fatigue resistance, as it is based on linear viscoelastic properties but not cracking resistance [35, 36]. Meanwhile, the inconsistency might be attributed to different effects of WMA additives on bitumen-aggregate adhesion. Further investigation on fatigue behavior of WARs will be conducted in future study, using other methods including linear amplitude sweep (LAS) test and four-point beam test [35, 37].

3.7 Summary

Table 8 briefly summarizes the workability and engineering performance of WAR mixtures compared to hot AR mixture. As shown, all WMA additives contributed to better workability. In terms of mechanical properties, no one WAR had superior performance in all aspects (rutting, fatigue and moisture susceptibility). Especially, the compromising effect of Evotherm-DAT on rutting and water resistance were mostly significant. By comparison, Sasobit worked best with the AR binder and mixture. It effectively enhances the workability of the AR mixture without obviously deteriorating other engineering performance. For field application, contractors may choose the right WMA technology depending on the targeted mechanical property or some special needs.

4 Findings and Recommendations

This paper presents a comprehensive laboratory study to characterize and compare the performances of WAR mixture prepared with five WMA additives, including Evotherm-DAT, Evotherm-3G, Sasobit, 56# paraffin wax and Aspha-min. Based on the test results on mixtures' workability, moisture susceptibility, stiffness modulus, dynamic modulus, and rutting and fatigue resistance, as well as the previous rheological property test results of the AR and WAR binders, the following major findings have been obtained

- All WMA additives selected in this study could reduce the production temperature of the AR mixture by at least 16 °C, without compromising its workability.
- The moisture damage resistances of all WAR mixtures are generally satisfactory. The ARE3G mixture performed the best, while the ARE mixture performed the worst.
- Both the stiffness modulus and dynamic modulus were affected by the type of WMA additives. The performance of the ARS mixture is closest to that of the AR mixture.
- All AR and WAR mixtures studied in this research showed better rutting and fatigue resistances compared with the SMA mixture with Pen 60/70 binder, which has been commonly used in Hong Kong.

The effects of the WMA additives on AR binder and AR mixture follow the same trend in most performance properties with only one exception, which is the fatigue resistance. It is recommended that additional fatigue performance tests, such as LAS test and four-point beam test, and investigation on the effect of WMA additives on the bitumen-aggregate adhesion be conducted to further validate the fatigue performance of WAR mixtures.

5 Acknowledgments

The authors sincerely acknowledge the funding support from the Hong Kong Research Grants Council (Project Number: 539113). Trademark or manufacturers' names appear in this paper only because they are considered essential to the object of this paper.

REFERENCES

[1] ASTM Standard D6114, Standard Specification for Asphalt-Rubber Binder, American Society for Testing and Materials, 2009.

[2] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and Portland cement concrete: an overview, Construction and Building Materials 67 (2014) 217-224.

[2] G.B. Way, K. Kaloush, K.P. Biligiri, Asphalt-rubber standard practice guide–an overview, Proceedings of asphalt rubber (2012) 23-40.

[3] Y. Huang, R. N. Bird, & O. Heidrich, A review of the use of recycled solid waste materials in asphalt pavements. Resources, Conservation and Recycling, 52 (2007), 58-73.

[4] H. Zhou, S. Holikatti, P. Vacura, Caltrans use of scrap tires in asphalt rubber products: a comprehensive review, Journal of Traffic and Transportation Engineering (English Edition) 1(1) (2014) 39-48.

[5] F. Xiao, P. W. Zhao, & S.N. Amirkhanian, Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives. Construction and Building Materials, 23 (2009), 3144-3151.

[6] D. Cheng, R.G. Hicks, T. Teesdale, Assessment of Warm Mix Technologies for Use with Asphalt Rubber Paving Applications, Transportation Research Board 90th Annual Meeting, 2011.

[7] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm mix asphalt: an overview, Journal of Cleaner Production 24 (2012) 76-84.

[8] F.A. Santagata, F. Canestrari, E. Pasquini, Mechanical characterization of asphalt rubber-wet process, Palermo: sn In: 4th International SIIV Congress, 2007.

[9] Y. Liu, S. Han, Z. Zhang, O. Xu, Design and evaluation of gap-graded asphalt rubber mixtures, Materials & Design 35 (2012) 873-877.
[10] L.P. Fontes, G. Triches, J.C. Pais, P.A. Pereira, Evaluating permanent deformation in asphalt rubber mixtures, Construction and Building Materials 24(7) (2010) 1193-1200.
[11] H. Yu, Z. Leng, Z. Gao, Thermal analysis on the component interaction of asphalt binders modified with crumb rubber and warm mix additives, Construction and Building Materials 125 (2016) 168-174.
[12] M. Abdelrahman, S. Carpenter, Mechanism of interaction of asphalt cement with crumb rubber modifier, Transportation Research Record: Journal of the Transportation Research Board (1661) (1999) 106-113.
[13] H. Yu, Z. Leng, F. Xiao, Z. Gao, Rheological and chemical characteristics of rubberized binders with non-foaming warm mix additives, Construction and Building Materials 111 (2016) 671-678.
[14] T. Billiter, R. Davison, C. Glover, J. Bullin, Physical properties of asphalt-rubber binder, Petroleum Science and Technology 15(3-4) (1997) 205-236.
[15] B.D. Prowell, G.C. Hurley, B. Frank, Warm-mix asphalt: Best practices, National Asphalt Pavement Association Lanham, Md, USA2011.
[16] Z. Leng, H. Yu, Z. Zhang, Z. Tan, Optimizing the mixing procedure of warm asphalt rubber with wax-based additives through mechanism investigation and performance characterization, Construction and Building Materials 144 (2017) 291-299
[17] A.M. Rodríguez Alloza, Asphalt rubber mixtures with warm mix asphalt additives, Doctoral Dissertation, Caminos, 2015.
[18] C.K.K. Akisetty, Evaluation of warm asphalt additives on performance properties of CRM binders and mixtures, Clemson University, 2008.

[19] P. Lerose Lane, Using Warm Mix Technology to Improve Applications of Asphalt Rubber in California. Report. Available at: http://www.asphaltpavement.org/big_files/11mwmx/Papers/WM57_Lane_Cheng.pdf

[20] P.V. Shivaprasad, F. Xiao, S.N. Amirkhanian, Evaluation of moisture sensitivity of stone matrix asphalt mixtures using polymerised warm mix asphalt technologies, International Journal of Pavement Engineering 13(2) (2012) 152-165.

[21] H. Ziari, M. Naghavi, R. Imaninasab, Performance evaluation of rubberised asphalt mixes containing WMA additives, International Journal of Pavement Engineering (2016) 1-7.

[22] A. Habal, D. Singh, Moisture Susceptibility of a Crumb Rubber Modified Binder Containing WMA Additives Using the Surface Free Energy Approach, GEO (2016) 245.

[23] D. Jones, R. Wu, C. Barros, J. Peterson, Research findings on the use of rubberized warm-mix asphalt in california, Asphalt Rubber, Roads of the Future (2012).

[24] F. Xiao, P.E. Wenbin Zhao, S.N. Amirkhanian, Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives, Construction and Building Materials 23(10) (2009) 3144-3151.

[25] Z. Chamoun, M.I. Souliman, E.Y. Hajj, P. Sebaaly, Evaluation of select warm mix additives with polymer and rubber modified asphalt mixtures, Canadian Journal of Civil Engineering 42(6) (2015) 377-388.

[26] D.X. Cheng, R.G. Hicks, PROJECT SUMMARY PAGE Date: October 3, 2012 Title: Summary of Rubber Modified Asphalt Product Specifications around the World.

[27] H. Yu, Z. Leng, Z. Zhou, K. Shih, F. Xiao, Z. Gao, Optimization of preparation procedure of liquid warm mix additive modified asphalt rubber, Journal of Cleaner Production 141 (2017) 336-345.

[28] Z. Suo, Evaluation of asphalt concrete pavement service life using 3D nonlinear finite element analysis and nonlinear fatigue damage model, The Hong Kong Polytechnic University, 2012.

[29] B. Choubane, G. Page, J. Musselman, Effects of water saturation level on resistance of compacted hot-mix asphalt samples to moisture-induced damage, Transportation Research Record: Journal of the Transportation Research Board (1723) (2000) 97-106.

[30] A. Cetin, Effects of crumb rubber size and concentration on performance of porous asphalt mixtures, International Journal of Polymer Science 2013 (2013). ID 789612.

[31] C.-T. Chiu, Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan, Resources, Conservation and Recycling 52(3) (2008) 522-532.

[32] K.E. Kaloush, M. Witczak, A. Sotil, G. Way, Laboratory evaluation of asphalt rubber mixtures using the dynamic modulus (E*) test, 82th Transportation Research Board Annual Meeting, Washington DC, 2003.

[33] D. Andrei, M. Witczak, M. Mirza, Development of a revised predictive model for the dynamic (complex) modulus of asphalt mixtures, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures, NCHRP (1999).

[34] S. Wu, Q. Ye, N. Li, H. Yue, Effects of fibers on the dynamic properties of asphalt mixtures, Journal of Wuhan University of Technology--Materials Science Edition 22(4) (2007) 733-736.

[35] F. Safaei, Specification of Linear Amplitude Sweep Test Temperature and Modeling Temperature Effects on Asphalt Binder Fatigue, (2016).

[36] L. Xue, W. Xie, Y. Wang, C. Wang, Characterizing Fatigue Failure Behavior of Modified Asphalt Binders from Linear Amplitude Sweep Test, (2017).

[37] F. Xiao, P.E.W. Zhao, S.N. Amirkhanian, Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives, Construction & Building Materials 23(10) (2009) 3144-3151.

LIST OF TABLES

TABLE 1 Properties of WMA Additives

Properties	**Evotherm-DAT**	**Evotherm-3G**	**Sasobit**	**$56^{\#}$ paraffin wax**	**Aspha-min**
Ingredients	Fatty amine derivatives, Alkylamines	Fatty amine derivatives, Alkylamines	Solid Saturated hydrocarbons	Solid saturated hydrocarbons	Zeolite, Water
State	Liquid	Liquid	Solid	Solid	Solid
Color	Caramel	Light-orange	Milky-white	Light-white	White
Odor	Amine-like	Amine-like	None	None	None
Density	>1.0g/cm^3	>1.0g/cm^3	0.622g/ cm^3	0.85g/ cm^3	1.57/cm^3
PH value	9-10	8-9	N/A	N/A	N/A
Boiling point	150-170 ^{o}C	150-170 ^{o}C	N/A	N/A	N/A
Melting point	N/A	N/A	105-110 ^{o}C	54^{o}C-58 ^{o}C	N/A
Water solubility	Partially soluble	Partially soluble	Insoluble	Insoluble	Insoluble
Dosage	5wt% of AR binder	0.5wt% of AR binder	3wt% of AR binder	1.5wt% of AR binder	0.3wt% of mixture

TABLE 2 Properties of Pen60/70, AR and WAR binders

	Pen 60/70	AR	ARE	ARE3G	ARS	ARW	ARMIN
Penetration at 25 ^{o}C (0.1mm)	66.5	40.2	77.4	44.7	33.1	48.3	42.5
Softening point (^{o}C)	48.5	64.5	46.5	68.2	87.4	62.3	66.0
Rotational viscosity at 135^{o}C/160^{o}C (cP)	481/-	10512/ 3388	6350/ 1813	7200/ 2750	5637/ 2025	5988/ 2487	-/-
G^{*}/sinδ at 64^{o}C (kPa)	4.012	24.187	6.794	15.145	38.021	10.758	19.355
G^{*}sinδ at 25^{o}C (MPa)	3.555	1.344	2.072	1.680	1.437	2.116	1.705
J_{nr}3200 at 64^{o}C (K/Pa)	3.473	0.288	1.36	0.426	0.2	0.528	0.37

**The rotational viscosities of ARMIN binder cannot be measured by traditional method because the reading kept changing due to the foaming effect*

TABLE 3 SMA10 gradation used in this study

BS Sieve Size	Design Data (%)	Passing Requirement (%)
14mm	100	100
10mm	96	92-100
5mm	35	28-42
2.36mm	26	19-33
75µm	9.8	7.8-11.8 (including 2% hydrated lime)

TABLE 4 Testing parameters, sample information and referred standards

Tests	Properties	Testing sample	Standard	Testing temperature
ITSM	Stiffness	SGC specimens (d=150mm, h=40mm, VIM=4%)	BS EN 12697-26	25°C
ITS	Moisture susceptibility	SGC specimens (d=100 mm, h=60mm, VIM=7%)	ASTM D6931	25°C
LWT	Rutting depth	Rutting slabs (300mm*300mm*50mm, VIM=4%)	BS EN 598-Part110	60°C
SPT	Dynamic modulus	SGC specimens (d=100 mm, h=150 mm, VIM=4%)	ASTM D3497	4°C, 20°C, 40°C
ITFT	Fatigue cycles	SGC specimens (d=100 mm, h=40 mm, VIM=4%)	BS EN DD ABF	25°C

TABLE 5 ITS results of AR and WAR mixtures

Mixture types	ITS_Dry (kPa) M_x (V_x)	ITS_Soaked (kPa) M_x (V_x)	TSR (%)	Air Void (%) M_x (V_x)
AR	852.63 (0.063)	725.48 (0.038)	85.09	7.11 (0.026)
ARE	676.97 (0.051)	530.06 (0.105)	78.30	7.04 (0.043)
ARE3G	783.87 (0.044)	692.98 (0.073)	88.40	7.26 (0.018)
ARS	940.74 (0.063)	772.54 (0.092)	82.12	7.13 (0.039)
ARW	838.79 (0.117)	625.91 (0.049)	86.54	7.20 (0.030)
ARMIN	843.39 (0.075)	693.09 (0.060)	82.18	7.05 (0.033)

TABLE 6 Results of wheel tracking tests

	AR	ARE	ARE3G	ARS	ARW	ARMIN
Rutting depth (mm)	1.69	3.75	2.34	1.58	2.89	1.83
Rutting rate (mm/h)	1.03	2.65	1.68	0.52	2.16	1.12
Loading period (mins)	45	45	45	45	45	45
Load level (N)	520	520	520	520	520	520

1 **TABLE 7 Material parameters of strain-fatigue equation**

2

Mixture types	$N_f = k_1(\xi)^{k_2}$ / $logN_f = logk_1 + k_2 log\xi$				Cycles at 100 micro strains
	$logk_1$	k_1	k_2	R^2	
AR	15.00943	1.02195E+15	-4.41648	0.8444	1.50E+06
ARE	13.05896	1.14541E+13	-3.37453	0.95901	2.04E+06
ARE3G	12.40743	2.55523E+12	-3.29446	0.88549	6.58E+05
ARS	11.90274	7.99356E+11	-3.18268	0.96721	3.45E+05
ARW	12.7882	6.14045E+12	-3.55507	0.9229	4.76E+05
ARMIN	11.46023	2.88556E+11	-2.90851	0.80283	4.40E+05

3

TABLE 8 Effect of WMA technologies on AR mixture performance

	Evotherm-DAT	Evotherm-3G	Sasobit	$56^{\#}$ paraffin wax	Aspha-min
Workability	↑	↑	↑	↑	↑
Rutting resistance	↓	↘	↗	↘	↘
Fatigue resistance	↗	↘	↘	↘	↘
Moisture susceptibility	↘	→	→	→	→

Note: ↑-enhanced, ↗- slightly enhanced, ↓-deteriorated, ↘slightly deteriorated, →- no obvious effect

LIST OF FIGURES

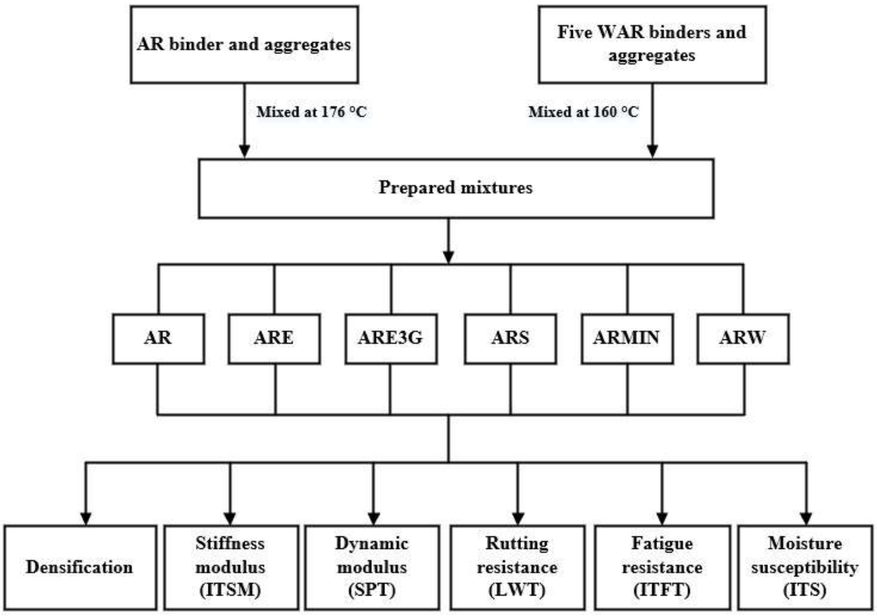

FIGURE 1 Experimental framework

FIGURE 2 Conducted tests: (a) ITSM; (b) SPT; (c) LWT; (d) ITS; (e) ITFT

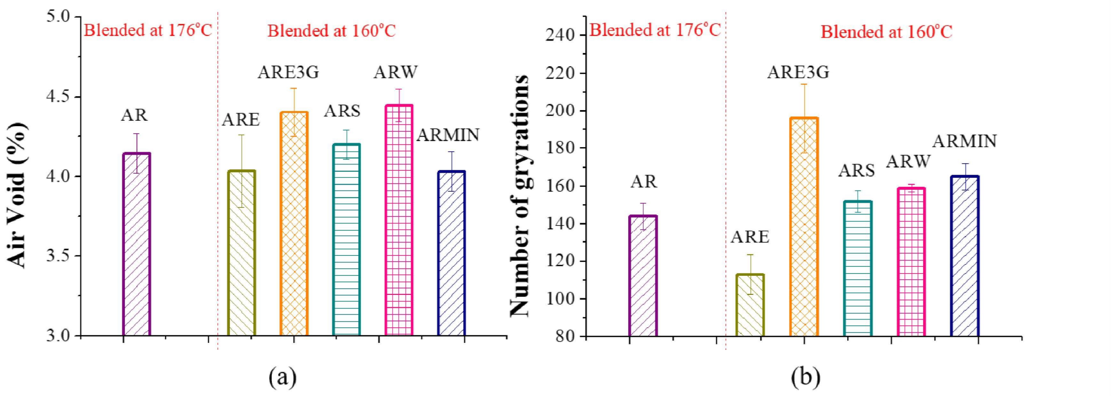

FIGURE 3 Workability evaluation: (a) Air void of Marshall specimens; (b) Gyration numbers of SGC specimens

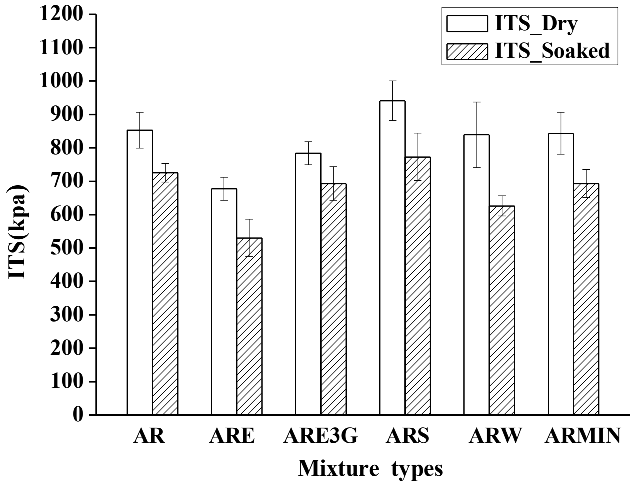

FIGURE 4 ITS test results

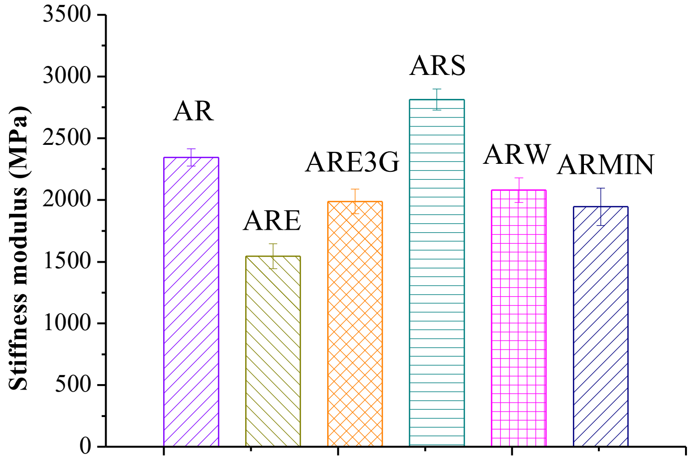

FIGURE 5 ITSM test results

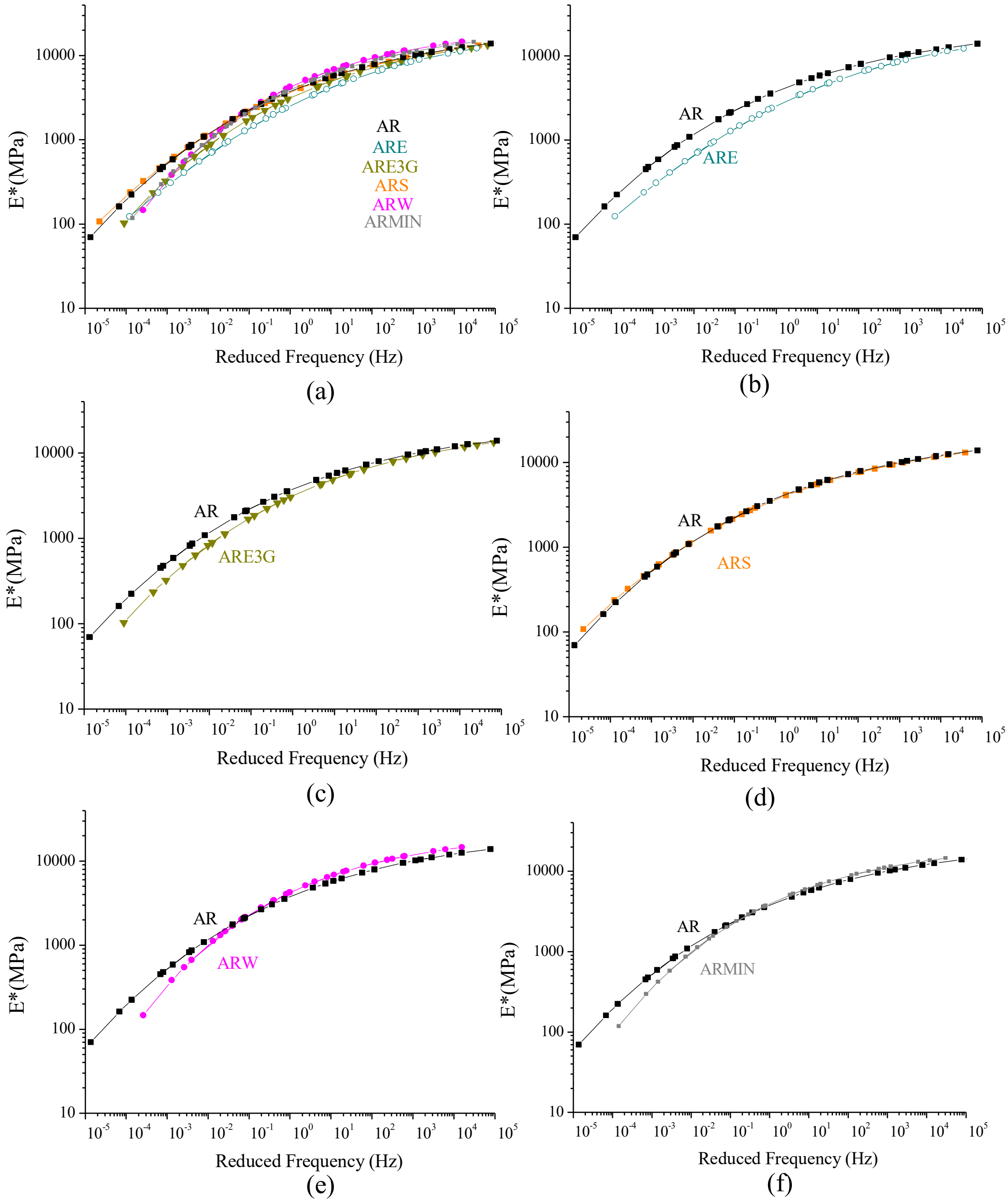

FIGURE 6 Master curves of dynamic modulus test results (reference temperature: 20°C): (a) All mixes; (b) AR &ARE; (c) AR&ARE3G; (d) AR&ARS; (e) AR&ARW; and (f) AR&ARMIN

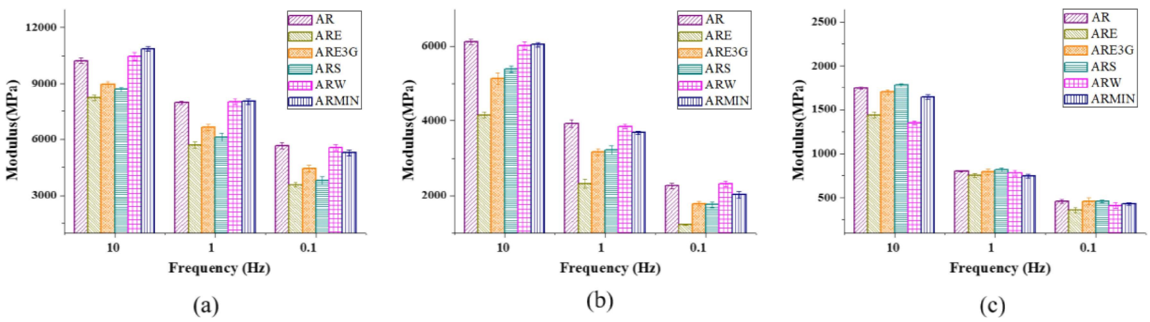

FIGURE 7 Isotherms curves at different testing temperature: (a) 4°C; (b)20°C; and (c) 40°C

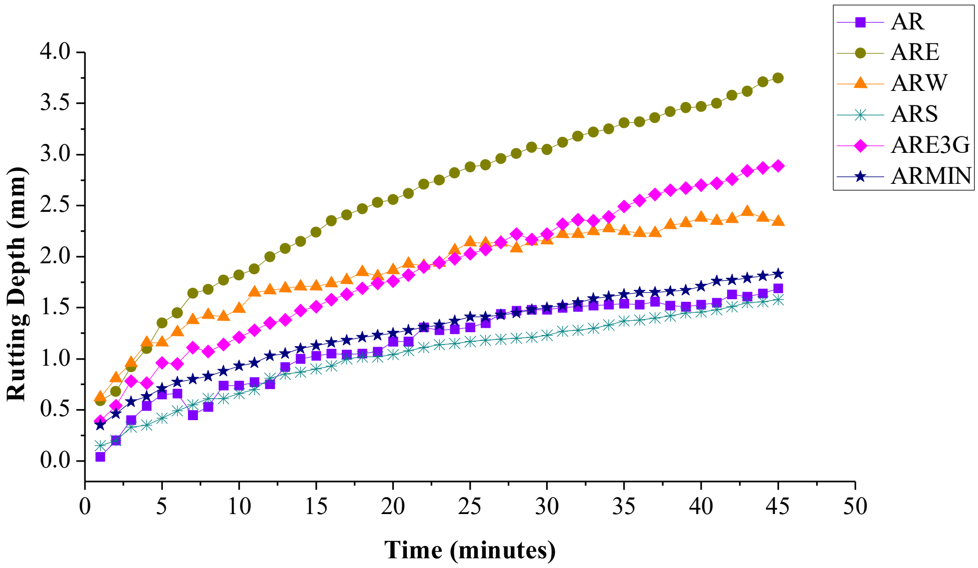

FIGURE 8 Cumulative rutting depths

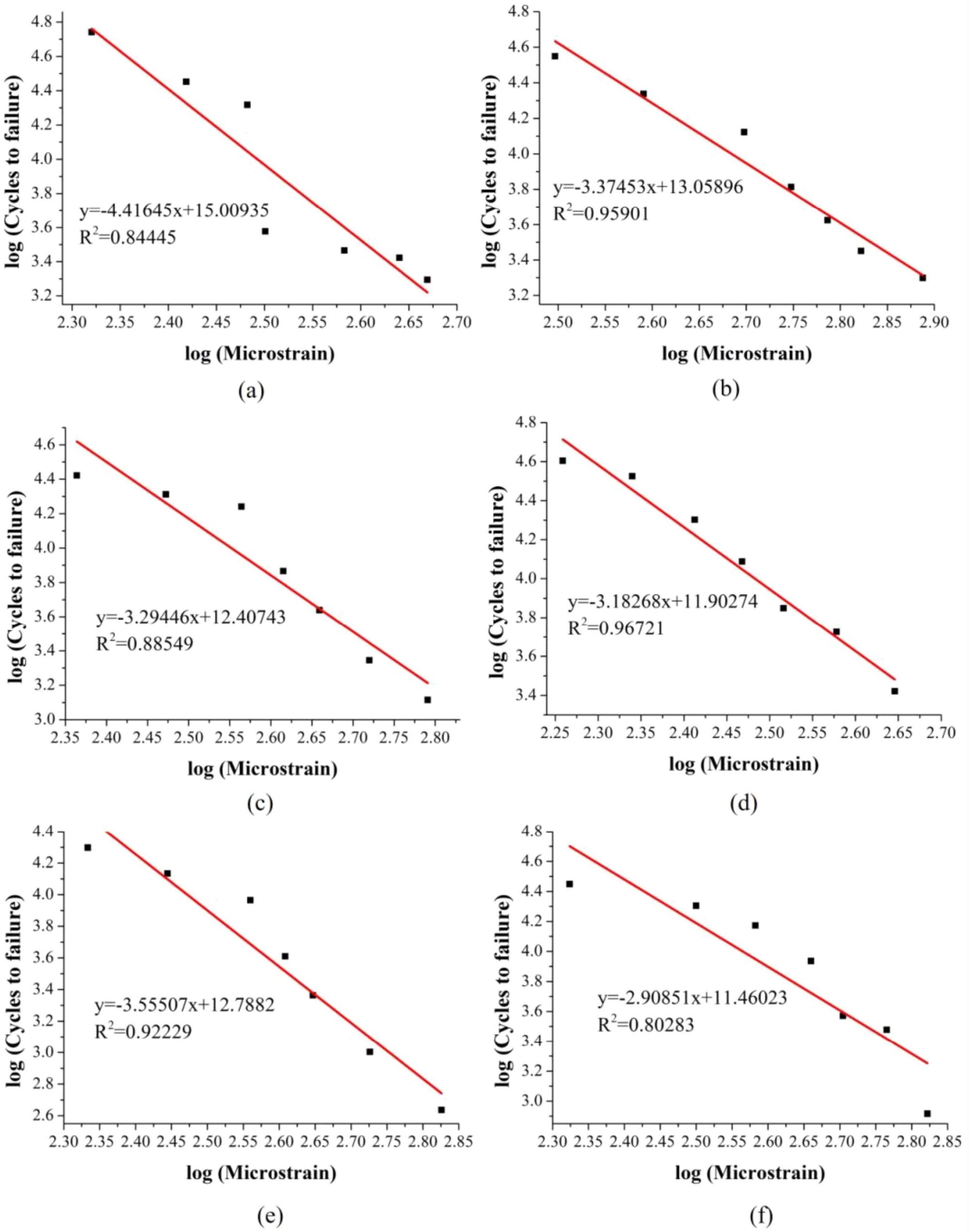

FIGURE 9 ITFT measurements for AR and WAR mixtures: (a) AR; (b) ARE; (c) ARE3G; (d) ARS; (e) ARW; and (f) ARMIN