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Effect of Mixing Sequence on Asphalt Mixtures Containing Waste Tire Rubber and Warm Mix Surfactants

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ABSTRACT: Crumb rubber modified asphalt mixture (CRMA) has gained rapid-growing interest as a sustainable paving material, because it allows value-added recycling of waste tire into durable and low-noise asphalt pavements. However, the poor workability of CRMA leads to higher construction temperature, which results in more energy consumption and hazardous emission. Surfactant, a typical warm mix asphalt additive, has been proven to be effective in alleviating the workability concern of CRMA without obviously deteriorating its mechanical properties. Nevertheless, performance of CRMA with surfactant may be influenced by the mixing sequence of different components (raw asphalt, crumb rubber, surfactant and aggregates), which unfortunately has not been well investigated yet. This study aims to address this issue by characterizing the engineering performance of warm CRMA prepared by six different mixing sequences. Properties including Marshall stability and flow value, workability, rheological property, rutting resistance, moisture sensitivity and fatigue resistance of prepared mixtures were measured and compared. Analytic hierarchy process (AHP) was employed to determine the optimal mixing sequence of warm CRMA considering the overall engineering performance. Test results showed that the effect of warm CRMA's mixing procedure on its engineering performance is noticeable. Earlier incorporation of surfactant additive had limited negative influence on mechanical properties of warm CRMA but allows for more energy saving during the production of rubberized asphalt binder. The AHP analysis results indicated that among the six mixing sequences, the optimal option is to make rubber absorb surfactant first, then incorporating the rubber-surfactant compound to raw asphalt and finally blending the modified binder to aggregates.

KEYWORDS: Crumb rubber modified asphalt mixture; Warm mix asphalt; Mixing procedure; Engineering performance

1. INTRODUCTION

Asphalt mixture has been extensively used for pavement construction owing to merits including improved smoothness, low traffic noise, easy maintenance and rapid construction (Leng et al., 2018; Zaumanis et al., 2018; Xu et al., 2019). The wide application of asphalt materials provides a potential approach to recycle industrial and domestic wastes, including plastic (Ahmadinia et al., 2011), waste packing tape (Yu et al., 2019a), seashells (Ruiz et al., 2018), cigarette butts (Mohajerani et al., 2017), reclaimed asphalt pavement (Zhao et al., 2012; Zhao et al., 2013; Song et al., 2018) and rubber tires (Liu et al., 2012). On one hand, the consumption of above refuse is an efficient way of waste management; on the other hand, the components within waste materials bring certain enhancement on performance of asphalt materials. Especially, the feasibility of using crumb rubber modifier (CRM) derived from waste vehicular tires as asphalt modifier has been demonstrated by both laboratory investigations and field surveys. (Moreno et al., 2013; Jia et al., 2015; Bai et al, 2016; Gong et al., 2018; Yu et al., 2018; Ling et al., 2019). In recent decades, many studies have been conducted to characterize the effect of CRM on the performance related properties of asphalt materials. These studies reported the superior service performance of CRMA in comparison with unmodified asphalt mixture and some other polymer modified asphalt mixtures. For example, based on both laboratory and field evaluation, Huang et al. reported that CRMA showed overall satisfied service performance including rutting, fatigue, and pavement roughness (Huang et al., 2002). A Brazilian study proven that the use of asphalt rubber (AR) binder significantly improved the rutting resistance of asphalt mixture (Fontes et al., 2010). Ding et al. (2017) found that the service performance, including rutting resistance, cracking resistance, moisture stability, and fatigue failure resistance, of CRMA is comparable to that of styrene–butadiene-styrene (SBS) modified asphalt mixture. In addition to the above-mentioned mechanical properties, addition of crumb rubber was also found to be able to reduce the noise generated by tire/pavement interaction (Vázquez et al., 2016) and to improve the anti-icing performance of asphalt pavement (Wei et al., 2016).

As known, two mixing process are available to prepare CRMA, namely, dry process and wet process (Chávez et al., 2019). In dry process, approximately 1% to 3% by weight of aggregate is substituted by crumb rubber. In wet process, crumb rubber works as a binder modifier. CRM is incorporated into raw asphalt as modifier and then the modified binder is blended to aggregates to prepare CRMA. By comparison, CRMA prepared by wet process exhibited superior engineering performance than that with dry process, as both the polymer modification and resilient particle effect of CRM are fully utilized (Ranieri et al., 2017; Chávez et al., 2019). However, it is worth noting that the incorporation of CRM significantly increases the viscosity of asphalt binder, resulting in higher mixing and paving temperature. Hence, the application of CRMA mixtures, especially those with wet process, carries environmental concerns and increases the energy consumption during its producing and paving process (Xiao et al., 2012). One effective approach to address the workability concern of CRMA is to incorporate warm mix asphalt (WMA) technology (Wei et al., 2016). Based on the working mechanism, WMA technologies can be grouped into three categories: foaming technologies, addition of organic additives, and addition of chemical additives (Rubio et al., 2012). WMA additives are able to enhance the workability of CRMA, but their influence on other properties varies (Xiao et al., 2010; Wang et al., 2012; Yu et al., 2018; Yu et al., 2019b). For instance, chemical WMA additives are liquid surfactants which reduce the fiction between asphalt binder and aggregate during their blending process. It is reported that surfactant can decrease the production temperature of CRMA by 15-30 ^{o}C without obviously deteriorating the mechanical properties (Paje et al., 2010; Cao and Liu, 2012; Oliveira et al., 2013; Yu et al., 2017).

Most of available studies on warm CRMA (WCRMA) focused on the effect of WMA type and dosage on binder and mixture properties. However, the mixing sequence of different components, which may exert significant difference on performance, has been ignored. For the preparation of WCRMA, apart from the conventional dry and wet process, the addition of WMA additive provides extra options of mixing sequences. Previous research reported that mixing sequence of warm mix asphalt affects the properties of warm AR binder (Paje et al., 2010; Yu et al., 2017). It was also proven that the early addition of surfactant additive had very marginal negative effect on rheological properties of AR binder (Yu et al., 2017). Nevertheless, limited studies focusing on optimizing the mixing sequence of WCRMA mixtures can be found.

To this end, this study aims to optimize the mixing sequences of CRMA mixtures with liquid surfactant additive. It is a follow-up study of the previous paper about mixing procedure of warm AR binder (Yu et al., 2017). In this paper, hot and warm CRMA mixtures were prepared with conventional dry/wet process and other four potential mixing sequences. The workability and service performance related properties including Marshall stability, stiffness modulus, moisture damage resistance, rutting resistance, and fatigue failure resistance of the prepared CRMAs and control asphalt mixture (unmodified asphalt mixture) were then compared to study the influence of mixing sequence. Analytic Hierarchy Process (AHP) was employed to determine the priority of mixing procedure considering the overall engineering performance of asphalt mixtures. It is believed that by means of optimizing the mixing procedure of CRMA, it might be able to prepare CRMA with optimal engineering performance and minimum energy consumption.

2. EXPERIMENTAL PROGRAM

2.1. Raw materials

The engineering properties of raw asphalt with a penetration grade of 60-80 (0.1 mm), which is chosen as the base binder in this study, are shown in Table 1.

Aggregate used in this study was basalt, provided by Central Fortune Creation (Canton) Roadway Technology Co., Ltd. Diabase filler, which is commonly used in southern China, was selected as mineral filler. SMA13 mixture with 4% designed air void was chosen to prepare hot and warm CRMA. The gradation of the aggregate is shown in Figure 1.

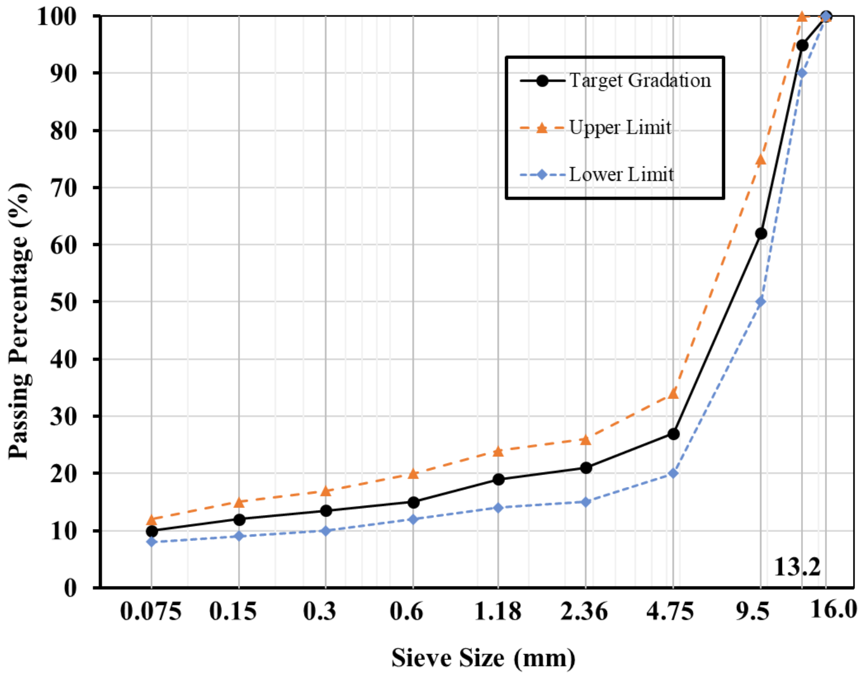

Figure 1. Aggregate Gradation

Physical properties of Evotherm-DAT can be found in previous studies (Yu et al., 2017; Yu et al., 2018). The dosage of the Evotherm-DAT was set as 5% by weight of asphalt binder according to the manufacture's recommendation. 40 mesh crumb rubber was used, and the dosage was 18% by weight of virgin binder. The gradation of crumb rubber is shown in Table 2.

Table 1. Engineering properties of virgin binder

Properties	**Unit**	**Pen60/70 binder**	**Specification**
Penetration	0.1mm	64.5	ASTM D5
Softening point	°C	48.9	ASTM D36
Solubility	%	99.9	AASHTO T 44-13
Separation difference	°C	0.2	BS EN 12697-15
Critical temperature when $G^*/\sin\delta$=1.0 kPa	°C	68.7	AASHTO TP 101

Rotational viscosity (135 °C/160 °C)	cp	480/170	AASHTO T316
After short-term aging			
Mass loss	%	-0.08	ASTM D2872
Critical temperature when G*/sinδ=2.2 kPa	°C	66	AASHTO TP 101
After long-term aging			
Critical temperature when G*sinδ=5 MPa	°C	22.5	AASHTO TP 101
Low-temp stiffness (-6/-12 °C)	MPa	121/222	AASHTO T313
m-value (-6/-12 °C)	-	0.386/0.316	AASHTO T313

Table 2. Gradation of crumb rubber

BS sieve size	**Passing rate**
0.6mm	100%
0.425mm	92.3%
0.3mm	58.7%
0.15mm	26.2%
0.075mm	12.5%

2.2. Asphalt mixture

Marshall mix design method was applied to design the asphalt mixture. The optimal asphalt binder content was determined as 6.7%. The volumetric properties of designed mixture can be found in a previous publication (Yu et al., 2019b).

As shown in Table 3, four mixing processes (Process A to Process D) were employed in this study to prepare WCRMA. In addition, dry- and wet- process were used to prepare hot mix CRMA. Control asphalt mixture was prepared with conventional hot mixing process, namely, blending virgin binder and aggregate at 160 ^{o}C. In this study, to focus on the effect of mixing sequence, each type of rubberized asphalt mixture used crumb rubber with same gradation and dosage.

Table 3. Involved mixing processes

Mixing Process	**Description**	**Mixture Label**
Conventional hot mixing process	Virgin binder was mixed with aggregate at 160 ^{o}C	Ctrl
Wet process	CR was added to virgin binder at 176 ^{o}C followed by high-speed shearing 60 minutes to prepare AR. The reaction time of 60 minutes was considered as suitable based on the preliminary studies (Yu et al., 2017). AR was then blended with aggregate at 176 ^{o}C, same production temperature of AR binder.	WM
Dry process	CR, aggregate and virgin binder were directly mixed at 160 ^{o}C to prepare asphalt mixture.	DM
A	The prepared AR, aggregates, and Evotherm-DAT were mixed together at 160 ^{o}C.	W-EM
B	CR, virgin binder and Evotherm-DAT were mixed directly using a high-speed shear mixer at 160 ^{o}C for 60 minutes to prepare ARE. Asphalt mixture was prepared by mixing the prepared ARE with aggregates at 160 ^{o}C.	AREM
C	Evotherm DAT were absorbed by CR by immersing CR in the Evotherm DAT for 24 hours (Yu et al., 2017). CR which absorbed Evotherm-DAT were blended to virgin binder at 160 ^{o}C for 60	REM

	minutes to prepare modified asphalt binder (ER-A). ER-A was added to aggregate at 160 ^{o}C to prepare asphalt mixture.	
D	CR, Evotherm-DAT, aggregate and asphalt binder were directly mixed together at 160 ^{o}C.	D-EM

2.3. Sample Preparation

In this study, four compaction methods, namely, Superpave gyratory compactor (SGC), standard Marshall method, and two types of segmented rolling compactors were employed to prepare test specimens. Based on experience obtained in previous studies, the blending temperature of WM was set at 176 ^{o}C, while that of other asphalt mixtures was set as 160 ^{o}C (Yu et al., 2018; Yu et al., 2019b). Cylindrical samples with the dimension of 150 mm in diameter and 95 ± 5 mm in height were compacted by SGC for moisture damage resistance test (AASTHO R 83, 2017). Superpave simple performance test was performed on test specimens (150 mm in height and 100 mm in diameter) cored from SGC-compacted samples. Cylindrical samples with the dimension of 101.5 mm in diameter and 63.5 mm in height for Marshall stability and flow value test were compacted using standard Marshall method. 300 mm × 300 mm × 50 mm asphalt mixture slabs were prepared using segmented rolling compactor for rutting test. Beam-shape specimens (380 mm × 50 mm × 63 mm) were extracted from the compacted slab (450 mm × 150 mm × 185 mm) for four-point bending fatigue test.

3. TESTING PROGRAM

3.1. Marshall stability and flow value tests

The conventional Marshall stability and flow values of all the asphalt mixture were obtained in accordance with ASTM D6927 (2015). Marshall stability refers to the maximum force the samples can withstand at the standard loading condition (a constant loading speed of 50mm/min). The amount of deformation of the samples when loaded to failure is expressed as the flow value. For each type of asphalt mixture, three replicate tests were performed.

3.2. Workability test

Since there is no standard test method for evaluating the workability of asphalt mixture, load cycles of Superpave gyratory compactor (SGC) was employed in this study to investigate the workability of asphalt mixtures prepared with various mixing procedures according to previous papers (Yu et al., 2018; Yu et al., 2019a). Loose asphalt mixture with same weight was compacted using SGC. 4 cm was set as the target height of compacted asphalt mixture and the corresponding load cycles were collected to reveal the workability of asphalt mixture (Yu et al., 2019a). Fewer cycles indicate a better workability of asphalt mixture. Three replicate tests were conducted in the workability test.

3.3. Superpave simple performance test

Simple performance test (SPT) was performed to characterize the dynamic modulus of asphalt mixtures according to AASHTO T342 (2011). The tests were performed at five temperatures: -10 ^{o}C, -4.4 ^{o}C, 21.1 ^{o}C, 37.8 ^{o}C, and 54.4 ^{o}C. At each temperature, the tests were performed at the following frequencies: 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz. The testing temperatures and frequencies were set according to the test standard AASHTO T342 (2011). The dynamic modulus, E*, was utilized to evaluate the rheological properties of asphalt mixture.

3.4. Moisture damage resistance test

The moisture damage resistance of asphalt mixture was determined by analyzing the indirect tensile strength (ITS) of asphalt mixture before and after freeze-thaw conditioning (ASTM D6931, 2017).

The conditioning program includes three phases. The prepared cylindrical specimens were first soaked into water at room temperature followed by placing into vacuum chamber until it achieves at vacuum saturation. The vacuum saturated specimens were then subjected to a freeze-thaw cycle including a -18 ^{o}C, 6h freezing process and a 60 ^{o}C, 24h thawing process. The specimens were placed into a 25 ^{o}C water bath for 2 hours before testing. The ITS of specimen before and after water conditioning was measured. The ITS ratio (ITSR), which is the ratio of specimen's ITS before and after water conditioning, was used to evaluate the moisture damage resistance of asphalt mixtures.

3.5. Rutting test

The rutting resistance performance of asphalt mixtures were investigated using loading wheel-tracking (LWT) test (ASTM D6372, 2015). The LWT test was performed at 60 ^{o}C which is regarded as the maximum service temperature of asphalt pavement. The wheel-tracking rate and rut depth were measured by applying a load to the single rubber wheel under 520 N for 45 minutes. Two parameters were used for rutting resistance characterization, 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).

3.6. Fatigue test

The fatigue response of asphalt mixture under repeated load were characterized using four-point bending (4PB) test (ASTM D7460, 2010). All the 4PB tests were performed at 15 ^{o}C. The fatigue life of the tested specimen was defined as the number of loading cycles when the modulus of the specimen attenuated by 50% of its initial modulus. The initial modulus was measured at 50th

loading cycle. Four microstrain levels, i.e., 400, 600, 800, and 1000, were selected to evaluate the fatigue response of asphalt mixture specimens.

Figure 2 presents the laboratory tests conducted in this study.

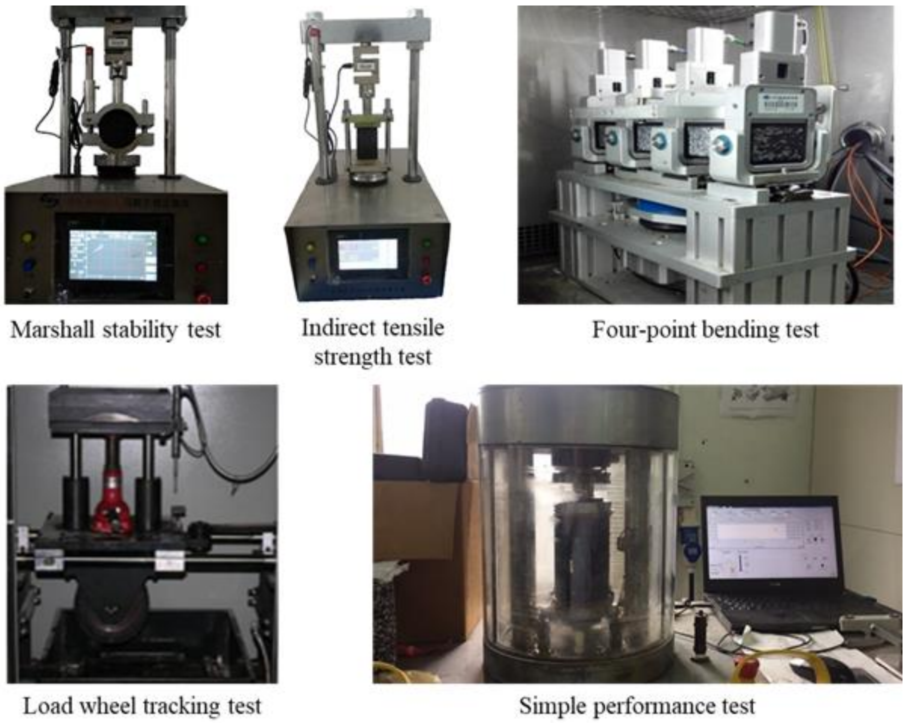

Figure 2. Experimental tests conducted in this study

3.7. Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) was developed by Thomas L. Saaty for organizing and analyzing complex decisions based on mathematic and psychology (Satty, 1990). AHP is a multi-criteria decision making approach, it ranges the factors affecting goal in a hierarchic structure descending from overall goal to criteria, sub-criteria and alternative in successive levels. In comparison with traditional decision tree, AHP is able to represent a different cut at the problem at each level. The procedure of using AHP decision process can be mainly separated into three steps: structure the problem as a hierarchy, evaluate the hierarchy, and establish priorities. The final decision is made based on the established priorities. The first step aims to provide an overall view with respect to the complex relationships inherent in the situation. At second step, the hierarchy is evaluated by means of pairwise comparison. Every goal, criterions, and alternatives are termed as nodes. Pairwise comparisons were performed on the nodes at each level. Specifically, the nodes at same level were compared, two by two, with respect to their contribution to the nodes above them. The pairwise comparison result, a_{ij}, represents the relative importance of node *i* to *j* and is given a corresponding intensity of importance. In AHP, there are mainly five scales of intensity of importance, namely, 1, 3, 5, 7, 9. From 1 to 9, the intensity of importance gradually increases. The intensities of 2, 4, 6, 8 were used to express intermediate values. The main scales for pairwise comparisons were listed in Figure 3.

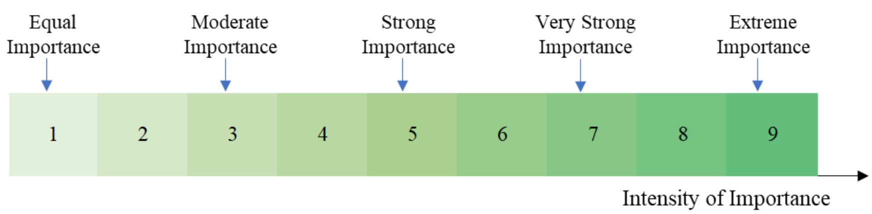

Figure 3. Main scales for pairwise comparison

If there are *n* alternatives, $A_1, \ldots, A_n$, whose weights are $\omega_1, \ldots, \omega_n$, respectively, then the pairwise comparison matrix, *A*, is desired to satisfy the following equation:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_n \end{array} \\ \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{bmatrix} \end{array} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix} = n \begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix} \qquad \text{Equation 1}$$

Where, $a_{ij} = \omega_i / \omega_j$, *n* is the size of matrix *A*. Mathematically, *n* is the eigenvalue of *A*, and ω is the associated eigenvector.

Given this, by solving equation, $AX = \lambda X$, the weights of alternatives can be obtained. Assume λ_{max} is the principal eigenvalue of A, X_{max} is the corresponding eigenvector, namely weight vector of the alternatives, then λ_{max} should satisfy Equation 2.

$$C.R. = \frac{C.I.}{R.I.} = \frac{\frac{\lambda_{max} - n}{n - 1}}{R.I.} < 0.1 \qquad \text{Equation 2}$$

where,

C.R. is consistency ratio,

C.I. is consistency index,

R.I. is random consistency index.

n is size of matrix.

4. RESULTS AND DISCUSSION

4.1. Marshall stability and flow value

Figure 4 presents the Marshall stabilities and flow values of asphalt mixtures. Marshall stability is an indicator of mixture performance at high temperature. Flow value relates to the stiffness of asphalt mixture. Asphalt mixture with a lower flow value is less susceptible to permanent deformation at high service temperature but more sensitive to low temperature thermal cracking. Both Marshall stability and flow value are involved in the Marshall design method as fundamental indicators.

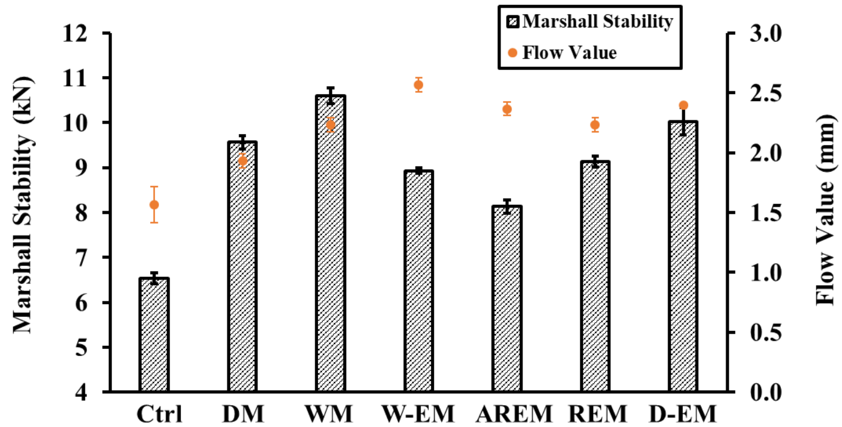

Figure 4. Marshall stability and flow values of asphalt mixtures

As can be seen in Figure 4, all CRMAs had higher Marshall stabilities than Ctrl, this is benefit from the addition of CRM. Among the CRMAs, Marshall stability changes varied along the different mixing sequences. WM exhibited the best high-temperature performance followed by DM, while that of AREM was the poorest. For WCRMAs, D-EM and AREM had the highest and lowest Marshall stability, respectively. Similarly, flow value was also affected by the mixing procedure. Among WCRMAs, W-EM presented the highest flow value, while that of REM was the lowest.

4.2. Workability

Workability refers to the difficulty of mixing and compacting asphalt mixture, the better the workability, the easier the mixing and compaction. Workability has been regarded as one of the critical indicators for asphalt mixture as it is related to the volumetric properties of asphalt mixture which affects the service performance of asphalt mixture. As abovementioned, the required compacting cycles of SGC were employed in this study to evaluate the compactiabilities of asphalt mixtures. More gyration numbers indicate more compaction energy and thus poorer compactiability. Figure 5 presents the required compacting cycles of different asphalt mixtures. As expected, because of the anti-compacting property of rubber particles in DM, it exhibited the highest gyrations number indicating the worst workability. The required compacting cycles of

CRMA with Evotherm DAT were obviously less than those without Evotherm DAT and similar to that of Ctrl. It verified the effectiveness of Evotherm DAT with respect to workability improvement of CRMA regardless of mixing sequence. However, the effect of mixing process on the workability cannot be ignored. REM and D-EM required the maximum and minimum load cycles, respectively with a difference of 13 cycles. While, the gyration numbers of three other WCRMAs were quite close together at around 158. Based on the results of required compacting cycles, the workability of the CRMAs can be ranked as DM<WM<REM<W-EM=AREM<D-EM.

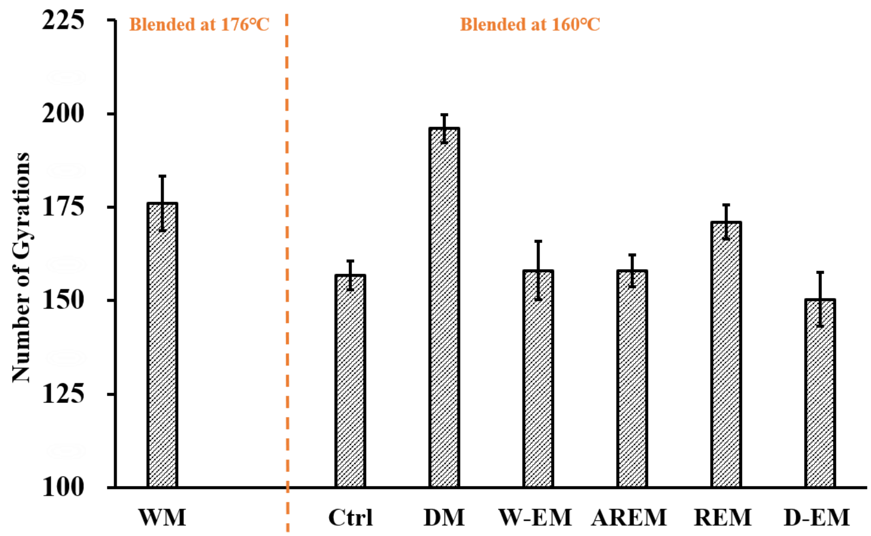

Figure 5. Load cycles of asphalt mixtures

4.3. Dynamic modulus

A strain range, within which asphalt mixture behaves as a linear visco-elastic material, is defined as the linear visco-elastic (LVE) region. Previous research documented that the dynamic modulus (ratio of stress to strain) of asphalt mixture within the LVE region has a good correlation with the service performance of asphalt mixture (Yu et al., 2019a). Generally, asphalt mixture with higher modulus at high service temperature (or low loading frequency) shows superior rutting resistance. Asphalt mixture with lower modulus at low service temperature (or high loading frequency) appears to be less susceptible to cracking. To investigate the overall performance of asphalt mixture within a wide frequency range, master curves of dynamic modulus at a reference temperature of 20 °C was established based on the dynamic modulus at different temperatures through the time-temperature superposition principle. Figure 6 illustrates the master curves of dynamic modulus of all asphalt mixtures.

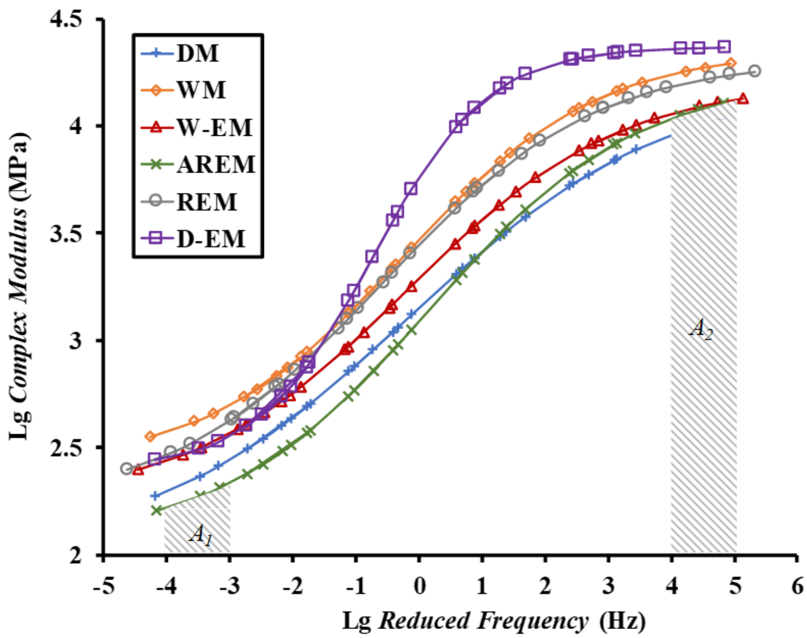

Figure 6. Master curves of dynamic modulus test results

As expected, the complex modules of asphalt mixtures are different at all frequencies revealing the effect of mixing process on overall rheological property of asphalt mixture. It can be observed that there is a significant difference between D-EM and other asphalt mixtures in terms of complex modulus at almost all frequencies. Among the other asphalt mixtures, the master curves of DM and AREM are nearly coincide indicating their similar rheological behavior. Similarly, it can be concluded that the performance of WM is comparable to that of REM. Moreover, it can be found that DM may present the best low-temperature performance, as it showed the lowest modulus at high frequencies. WM may present the best high-temperature performance because its dynamic modulus at low frequencies was the highest.

The area enclosed by the master curve and reduced frequency reveals the performance of asphalt mixture within the corresponding frequency range. For instance, area, *A1*, enclosed by low-frequency (1E-4 Hz to 1E-3 Hz) and AREM's master curve indicates the high-temperature performance of AREM. Similarly, *A2* shows AREM's low-temperature performance. A dimensionless indicator *S* was used to quantify the overall rheological performance of asphalt mixture in this study. *S* is defined by Equation 3. Asphalt mixture with higher *S* presents a better overall rheological performance.

$$S = \frac{A_1}{A_2} \qquad \text{Equation 3}$$

A_1, A_2 and *S* of asphalt mixtures are listed in Table 4. Darker color indicates better performance. Same as Figure 6, WM and DM had the best high-temperature and low-temperature performance, respectively. Based on *S*, it was found that WM performed the best overall performance followed by W-EM, and REM. The overall performance of AREM was the poorest one.

Table 4. Overall rheological performance of asphalt mixtures

Asphalt mixture	A1	A2	S
DM	2.364	4.006	0.590
WM	2.631	4.268	0.616
W-EM	2.495	4.095	0.609
AREM	2.269	4.08	0.556
REM	2.539	4.171	0.609
D-EM	2.492	4.363	0.571

4.4. Moisture damage resistance

Moisture damage is one of the main distresses which significantly decreases the service life of asphalt pavement. Moisture penetrates into the asphalt mixture through cracks and connected pores. As a consequence of freezing, these penetrated moistures swell and deforms the asphalt mixture leading to crack propagation and an increase in the connected pores. This process deteriorates the mechanical properties of asphalt mixture. ITSR reflects the moisture damage resistance of asphalt mixture. Higher ITSR refers to superior moisture damage resistance. Figure 7 presents the ITS of asphalt mixture before and after freeze-thaw cycle as well as the corresponding ITSR.

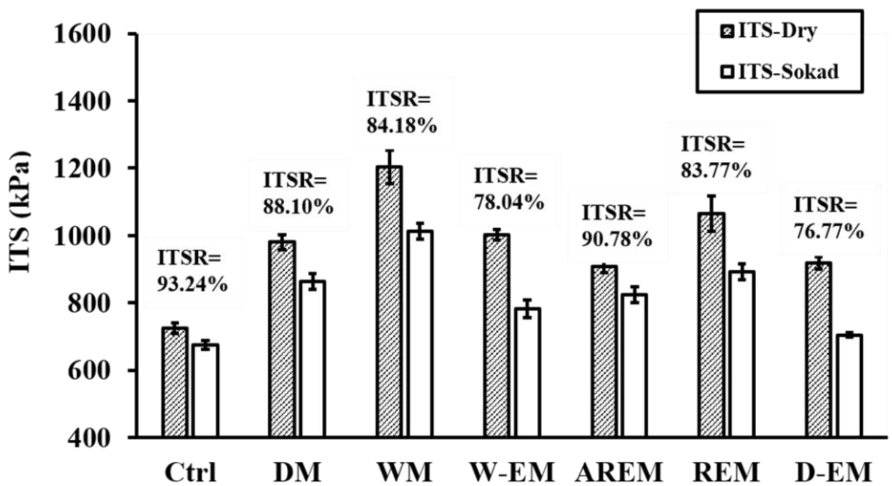

Figure 7. ITS of asphalt mixtures before and after freeze-thaw cycle

As can be observed, regardless of the moisture condition of asphalt mixture, ITS of CRMAs were higher than that of Ctrl. This is because of the stiffness enhancing effect of CRM. The ITS changed with the changing of the mixing procedure indicating the non-negligible influence of mixing procedure on stiffness of asphalt mixture. Although the ITSR values of all the asphalt mixtures ranged from around 77% to 93%, which were much higher than the minimum threshold value (70 % to 80 %), the ISTR values of CRMAs were lower than that of Ctrl. By comparing the ITSR values among all the CRMAs, it was found that mixing procedure affected the moisture damage resistance of asphalt mixture. AREM and D-EM exhibited the highest and the lowest ITSR value, respectively. This finding could be explained by the variation of adhesive effect between asphalt binder and aggregate because moisture is easier to penetrate to asphalt mixture with worse bonding effect. Therefore, asphalt mixture with worse bonding effect may shows lower ISTR value. The ranking of CMRAs prepared with different mixing processes with respect to moisture damage resistance performance from low to high was D-EM, W-EM, REM, WM, DM and AREM.

4.5. Rutting resistance

Rutting occurs on the wheel path of pavement. It attributes to the cumulative permanent deformation of pavement resulting from repeated wheel loads at high temperature. Rutting mainly happens in summer when the capacity of asphalt mixture is lower and is more sensitive to wheel load. Therefore, rutting resistance is an important indicator to evaluate the high-temperature of asphalt mixture. Higher rut depth reveals poorer rutting resistance. Figure 8 presents the results of the WLT test.

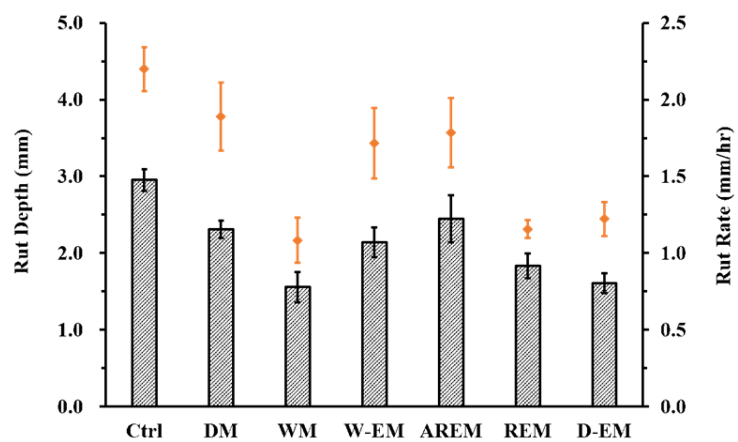

Figure 8. Rut depth and rut rate of asphalt mixtures

Based on the rut depth and rut rate, it can be found that adding CRM helps to improve the rutting resistance of asphalt mixture. Based on the measured rut depth, the rutting resistance of asphalt mixtures, from low to high, can be ranked as Ctrl, AREM, DM, W-EM, REM, D-EM, WM. Based on the rut rate, the ranking was Ctrl, DM, AREM, W-EM, D-EM, REM, WM. Again, this finding demonstrated the effect of mixing process on the service performance of CRMAs.

4.6. Fatigue performance

During the service life of asphalt pavement, fatigue cracking is a primary mode of failure that is caused by undergoing millions of repeated load applications. Fatigue cracking occurs if the applied loads exceed the designed capacity of fatigue resistance of the asphalt mixture. These cracks will quickly extend to a much larger area. Fatigue cracking brings considerable cost in maintenance and rehabilitation, reduce the ride quality (due to the increased roughness of pavement surface) and significantly decrease the pavement's service life. Therefore, it is of fundamental to assess the fatigue performance of asphalt mixtures. Figure 9 presents the measured fatigue life of asphalt mixtures at different strain levels. Obviously, the fatigue life of all the asphalt mixtures decrease as the increase of strain amplitude. The fatigue line of REM, WM, AREM were in a similar region indicating the corresponding CRMAs exhibited similar fatigue performance under strain loadings.

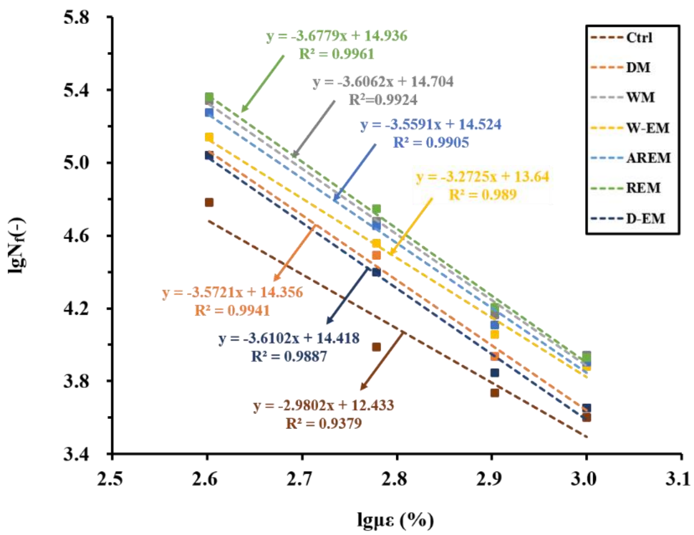

Figure 9. N_f vs. strain of asphalt mixtures

The classical fatigue relationship model described in Monismith et al. (1961) is reproduced in Equation 4.

$$N_f = a\left(\frac{1}{\varepsilon}\right)^b \qquad \text{Equation 4}$$

where, *a* and *b* are material specific constants, which are considered to be related to the fatigue property of asphalt mixture, determined by recession analysis. ε is strain level.

Constant a and b of different asphalt mixtures are listed in Table 5.

Table 5. Values of a and b of different asphalt mixtures

Asphalt mixture	a	b
Ctrl	6.89E-10	4.10E+00
DM	6.75E-07	3.30E+00
WM	2.97E-08	3.79E+00
W-EM	4.98E-07	3.37E+00
AREM	1.11E-07	3.60E+00
REM	1.59E-07	3.58E+00

The area enclosed by the N_f-strain curve and lgμε, as shown in Figure 10, was used as an indicator to quantify the differences between the asphalt mixtures with respect to the entire fatigue performance. The larger the area, the better the fatigue resistance. As can be seen, the fatigue resistance of Ctrl is much poorer than that of CRMAs, which proved the positive effect of CRM on fatigue resistance of asphalt mixture. Among all the CRMAs, fatigue resistance of DM and D-EM were poorer than that of the rest CRMAs.

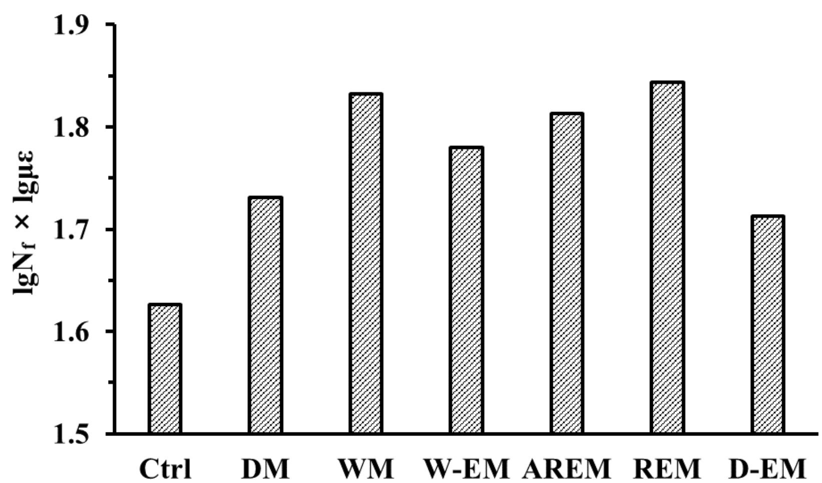

Figure 10. Fatigue performance of asphalt mixtures

4.7. Analytic Hierarchy Process

AHP was used in this study to determine the optimal mixing procedure of CRMA considering the overall service performance. As shown in Figure 11, optimal mixing procedure was set as goal (G), six performance related indicators, including rutting resistance (C1), fatigue performance (C2), overall rheological performance (C3), moisture damage resistance (C4), Marshall stability (C5), and workability (C6) were set as criterions (C), mixing procedures were set as alternatives (A).

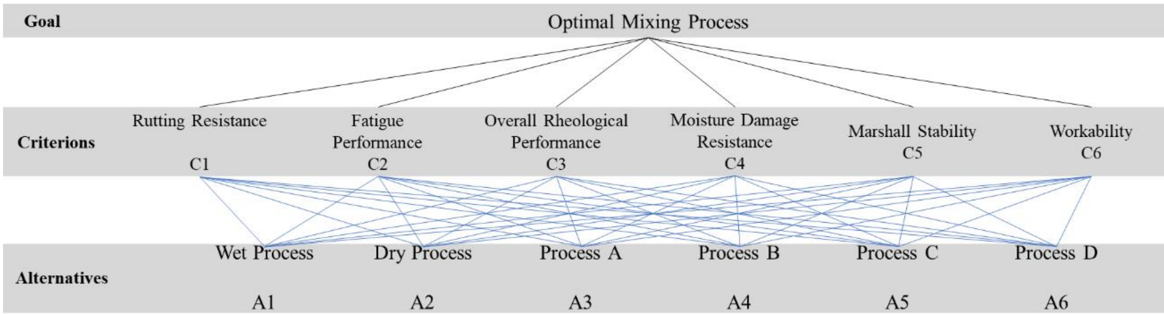

Figure 11. Diagram of hierarchy

In southern China, rutting performance is the most critical indicator in terms of pavement designing and construction followed by fatigue performance and overall rheological behavior. Therefore, the ranking of the six performance related indicators with respect to importance is rutting performance > fatigue performance = overall rheological performance > moisture damage resistance > Marshall stability > workability. Thus, the corresponding pairwise comparison matrix can be obtained as shown below:

$$G = \begin{bmatrix} 1 & 2 & 2 & 3 & 7 & 9 \\ 1/2 & 1 & 1 & 2 & 6 & 7 \\ 1/2 & 1 & 1 & 2 & 6 & 7 \\ 1/3 & 1/2 & 1/2 & 1 & 3 & 5 \\ 1/7 & 1/6 & 1/6 & 1/3 & 1 & 3 \\ 1/9 & 1/7 & 1/7 & 1/5 & 1/3 & 1 \end{bmatrix}$$

The principle eigenvalue of matrix G (λ_G) and the corresponding eigenvector (X_G) were then calculated:

$$\lambda_G = 6.1296$$

$$X_G = [0.7262, 0.4465, 0.4465, 0.2470, 0.0984, 0.0566]^T$$

After normalization, X_G can be rewritten as follows:

$$\omega_G = [0.3593,0.2209,0.2209,0.1222,0.0487,0.0280\ ]^T$$

Since the consistency ratio of matrix G was 0.021, verified the consistency of pairwise comparison matrix, the priorities of six performance-related indicators is 0.3593, 0.2209, 0.2209, 0.1222, 0.0487, 0.0280, respectively.

Pairwise comparisons were then performed on the alternatives, namely, A_1 to A_6, for determining their priorities to six indicators based on the experimental results. The matrixes of pairwise comparison of the alternatives are given below according to the quantified differences in terms of importance to six indicators.

$$C_1 = \begin{bmatrix} 1 & 4 & 2 & 9 & 2 & 1 \\ 1/4 & 1 & 1/2 & 2 & 1/3 & 1/4 \\ 1/2 & 2 & 1 & 4 & 1/2 & 1/2 \\ 1/9 & 1/2 & 1/4 & 1 & 1/7 & 1/9 \\ 1/2 & 3 & 2 & 7 & 1 & 1 \\ 1 & 4 & 2 & 9 & 1 & 1 \end{bmatrix} C_2 = \begin{bmatrix} 1 & 4 & 2 & 1 & 1 & 8 \\ 1/4 & 1 & 1/2 & 1/3 & 1/4 & 2 \\ 1/2 & 2 & 1 & 1/2 & 1/2 & 5 \\ 1 & 3 & 2 & 1 & 1 & 7 \\ 1 & 4 & 2 & 1 & 1 & 9 \\ 1/8 & 1/2 & 1/5 & 1/7 & 1/9 & 1 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} 1 & 2 & 1 & 9 & 1 & 3 \\ 1/2 & 1 & 1 & 6 & 1 & 2 \\ 1 & 1 & 1 & 8 & 1 & 3 \\ 1/9 & 1/6 & 1/8 & 1 & 1/8 & 1/3 \\ 1 & 1 & 1 & 8 & 1 & 3 \\ 1/3 & 1/2 & 1/3 & 3 & 1/3 & 1 \end{bmatrix} C_4 = \begin{bmatrix} 1 & 1 & 3 & 1/2 & 1 & 5 \\ 1 & 1 & 4 & 1 & 2 & 8 \\ 1/3 & 1/4 & 1 & 1/5 & 1/3 & 2 \\ 2 & 1 & 5 & 1 & 2 & 9 \\ 1 & 1/2 & 3 & 1/2 & 1 & 5 \\ 1/5 & 1/8 & 1/2 & 1/9 & 1/5 & 1 \end{bmatrix}$$

$$C_5 = \begin{bmatrix} 1 & 2 & 3 & 9 & 2 & 1 \\ 1/2 & 1 & 2 & 6 & 1 & 1 \\ 1/3 & 1/2 & 1 & 4 & 1 & 1/2 \\ 1/9 & 1/6 & 1/4 & 1 & 1/4 & 1/7 \\ 1/2 & 1 & 1 & 4 & 1 & 1/2 \\ 1 & 1 & 2 & 7 & 2 & 1 \end{bmatrix} C_6 = \begin{bmatrix} 1 & 5 & 1/2 & 1/2 & 1 & 1/2 \\ 1/5 & 1 & 1/8 & 1/8 & 1/5 & 1/9 \\ 2 & 8 & 1 & 1 & 1 & 1 \\ 2 & 8 & 1 & 1 & 1 & 1 \\ 1 & 5 & 1 & 1 & 1 & 1/2 \\ 2 & 9 & 1 & 1 & 2 & 1 \end{bmatrix}$$

The principle eigenvalues (λ) of pairwise comparison matrixes and the corresponding C.R. are listed in Table 6.

Table 6. Principle eigenvalues and C.R. of pairwise comparison matrixes

	C1	C2	C3	C4	C5	C6
λ	6.046	6.017	6.047	6.048	6.067	6.071
C.R.	0.007	0.003	0.007	0.008	0.011	0.011

As can be seen, the C.R. of all the pairwise comparison matrixes are smaller than 0.1 revealing the consistency of the matrixes. The corresponding priority eigenvectors, ω_{Ci}, of six alternatives can be calculated:

$$\omega_{C1} = [0.2969, 0.0670, 0.1281, 0.0314, 0.2153, 0.2613\ ]^T$$

$$\omega_{C2} = [0.2590, 0.0681, 0.1347, 0.2425, 0.2642, 0.0314\ ]^T$$

$$\omega_{C3} = [0.2595, 0.1807, 0.2250, 0.0282, 0.2250, 0.0815\ ]^T$$

$$\omega_{C4} = [0.1817, 0.2597, 0.0605, 0.3051, 0.1603, 0.0327\ ]^T$$

$$\omega_{C5} = [0.2967, 0.1850, 0.1130, 0.0316, 0.1364, 0.2372\ ]^T$$

$$\omega_{C6} = [0.1266, 0.0276, 0.2174, 0.2174, 0.1624, 0.2487\ ]^T$$

The priorities of alternatives, namely, mixing sequence, to the overall service performance of asphalt mixture was calculated in accordance with Figure 11. The calculated priorities with respect to the overall performance of asphalt mixture were presented in Figure 12. Asphalt mixture prepared by mixing procedure with higher priority shows better overall service performance.

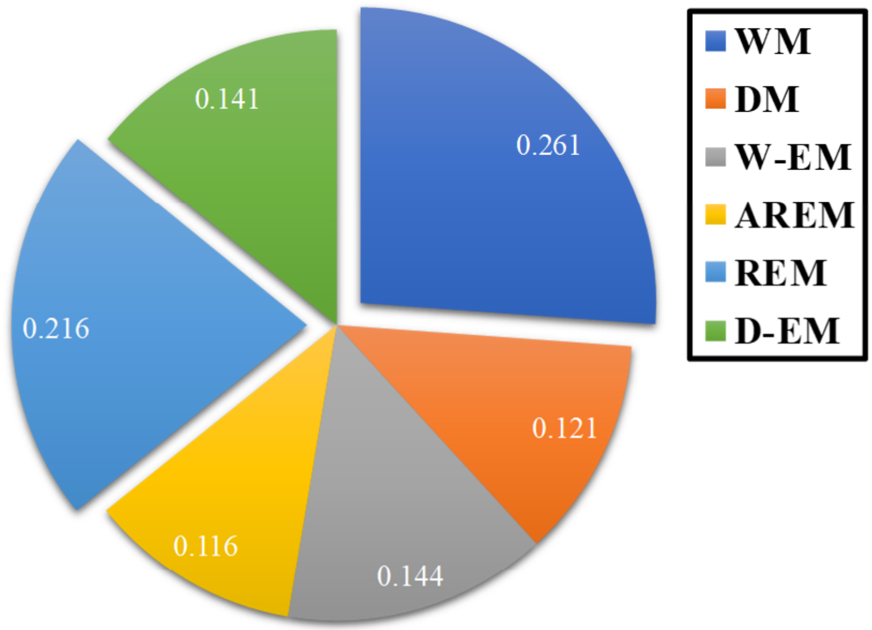

Figure 12. Priorities of mixing procedure

The data presented in this figure indicates that the conventional wet mix CRMA shown the top priority followed by REM, while AREM had the lowest priority. Among all the WCRMAs, REM had the first priority revealing the best overall service performance. In addition, the priority of W-EM was similar to that of D-EM revealing the similar overall service performances.

5. SUMMARY AND FINDINGS

In this study, the differences among the engineering performance including workability, high-temperature performance, moisture damage resistance and fatigue performance of CRMAs resulting from varied mixing sequences were investigated through laboratory experiments. Based on the experimental results, the differences of CRMAs in terms of engineering performance were quantified. The optimal mixing procedure of CRMA in terms of best overall engineering performance was determined by means of AHP. The following summarizes the major findings of this study:

- Crumb rubber enhances the high-temperature and fatigue performance of asphalt mixture. However, it has opposite effect on the moisture damage resistance of asphalt mixture.
- The incorporation of surfactant additive, Evotherm-DAT, slightly compromises the engineering performance of CRMA.
- For the warm rubberized asphalt mixtures, the effect of the mixing sequence on their engineering performance is significant.
- The optimal preparing sequence to produce warm rubberized asphalt is to make rubber absorb the liquid surfactant first, then incorporating the modified rubber to raw asphalt and finally blending the warm asphalt rubber binder to aggregates.

Finally, this study proves that the effect of mixing sequence on engineering performance of warm rubberized asphalt mixture is significant. However, it is worth noting that this study focuses on samples with liquid surfactant additive. The effects of mixing sequence on rubberized mixtures with other types of WMA additives like FT-wax and zeolite will be investigated in future studies.

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FIGURE CAPTIONS

1. Aggregate gradation.
2. Experimental tests conducted in this study.
3. Main scales for pairwise comparison.
4. Marshall stability and flow values of asphalt mixtures.
5. Load cycles of asphalt mixtures.
6. Master curves of dynamic modulus test results.
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8. Rut depth and rut rate of asphalt mixtures.
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10. Fatigue performance of asphalt mixtures.
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TABLE CAPTIONS

1. Engineering properties of virgin binder.
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3. Involved mixing processes.
4. Overall rheological performance of asphalt mixtures.
5. Values of a and b of different asphalt mixtures.
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