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Decision support for selecting optimal method of recycling waste tire rubber into wax-based warm mix asphalt based on fuzzy comprehensive evaluation

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A B S T R A C T

Recycling crumb rubber (CR) derived from waste vehicle tire as asphalt modifier is an effective waste management approach with both engineering and environmental merits. However, the high viscous asphalt rubber (AR) brings higher energy consumption and hazardous construction emission. Wax-based warm mix asphalt (WMA) additive has proven to be able to alleviate these concerns. Application of WMA additives enriches the methods of recycling CR into asphalt. Preliminary investigations documented the effects of CR recycling methods on the service performance of warm crumb rubber modified asphalt mixture (WCRMA). Therefore, making a decision on the optimal recycling method considering the overall service performance is necessary. Nevertheless, there are limited studies focusing on the recycling method assessment and decision-making approach. To fill this gap, WCRMAs with different crumb rubber recycling methods were prepared and tested in laboratory. The effect of the recycling method on the overall service performance of WCRMAs was characterized. A fuzzy comprehensive evaluation (FCE) method was employed to quantify the performance grade of asphalt mixtures according to fuzzy logic. The weight matrix of all the service properties was developed based on the Analytic Hierarchy Process (AHP) under the considering of the circumstance of southern China. The experimental work revealed the significant influence of the recycling method on the service performance of WCRMAs. By means of the FCE method, this study suggested that for southern China with hot and humid climate, the optimal method of recycling CR into wax-based WCRMA is mixing AR and Sasobit first followed by incorporating them into aggregate. In rainy regions, asphalt mixture produced by directly mixing AR, Sasobit, and aggregate at 160 °C may perform better because it showed the best moisture damage resistance and good overall performance.

1. Introduction

Asphalt mixture has been used as a paving material of expressways and urban streets worldwide. While offering a significant contribution to the economy and society, the environmental influences of asphalt pavement in all periods including construction, operation, and maintenance are not negligible. With increasing interest in sustainable infrastructure, the construction of asphalt pavement is suggested to follow reclaim, recycle and reduce (3R) principles (Cao et al., 2019b; Vidal et al., 2013). Generally, reclamation in pavement engineering refers to the process of reclaiming road materials from loss or from a less useful condition; recycling involves processing waste materials from other fields into useful pavement products; and reduce means consuming less energy and bringing fewer pollutants to the environment during the life cycle period. In recent years, many sustainable asphalt paving technologies fitting “3R” were developed and applied (Ameri et al., 2018; Jahanbakhsh et al., 2019; Xiao et al., 2018; Yu et al., 2019b; Yu

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et al., 2019a).

Recycling end-of-life vehicle tires into asphalt pavement meets both the “recycle” and “reduce” principles (consuming waste tires and alleviating traffic noise) (Hosseinnezhad et al., 2019; Ren et al., 2020). In this green paving technology, crumb rubber (CR) particles shredded from waste tire are incorporated with asphalt mixture either to replace part of aggregates or work as an asphalt binder modifier (Hernandez-Olivares et al., 2009). The positive effect of CR on performance enhancement of asphalt pavement has been documented by researchers. The incorporation of CR enhances the fatigue resistance, high-temperature performance, moisture stability, anti-cracking property of asphalt pavement (Youssf et al., 2016). However, crumb rubber modified asphalt (CRMA) pavement is criticized for its high-construction temperature due to the high-viscosity of asphalt rubber (AR). The construction temperature of CRMA pavement is 30–50 °C higher than that of conventional hot mix asphalt (HMA) pavement (Cao et al., 2019a). Higher construction temperature results in not only more energy consumption and hazardous emissions but also severe short term aging of asphalt materials (Liang et al., 2017; Yang et al., 2018).

Warm mix asphalt (WMA) technology, which meets the “reduce” principle, has been developed to alleviate the energy and environmental concerns of asphalt pavement. Both laboratory investigations and in-site field surveys have been conducted to evaluate the effects of WMA technologies on the environmental and mechanical properties of asphalt mixture (Capitão et al., 2012; Rubio et al., 2012). Evident energy saving and environmental impact reduction were obtained by field survey and life cycle assessment (LCA) (Cao et al., 2019a; Farina et al., 2017). Experimental results revealed that WMA technologies can reduce the construction temperature by 15–30 °C (Almeida-Costa and Benta, 2016). In addition, the engineering performance of the warm mix asphalt mixture is comparable to that of the conventional HMA (Song et al., 2018). Given this, WMA technology could be a solution to the environmental and construction issues of CRMA. According to the different working mechanisms, WMA technologies can be separated into three groups: foaming technologies, the addition of organic additives, and the addition of chemical additives (Rubio et al., 2012).

Previous studies have been conducted to evaluate the feasibility of incorporating these WMA technologies to CRMA, which mainly focused on the high- and low-temperature performance, fatigue resistance, moisture susceptible, aging resistance, workability and life-cycle energy consumption of warm CRMAs (Cao et al., 2019a; Xiao et al., 2009; Xu et al., 2013; Yu et al., 2018a). These studies indicated that although the service properties of warm CRMA (WCRMA) varies depending on the WMA additives, the performance of WCRMAs is comparable to the conventional HCRMAs. Moreover, it was reported that adding WMA evidently reduces the construction temperature as well as the life-cycle energy consumption of CRMA (Rodríguez-Alloza et al., 2015). In addition to the engineering performance, researchers employed chemically and mechanically experimental methods to gain a deeper understanding of the performance-enhancing mechanism of WCRMA. These studies mainly focused on the internal structure of AR, the response of CR and AR against the environmental and mechanical loading as well as the reaction and interface properties among CR, WMA additive, base binder and aggregate (Rodríguez-Alloza and Gallego, 2017; Shen et al., 2017; Wang et al., 2016; Yu et al., 2016).

By comparison, research on the methods of recycling CR into asphalt is relatively limited. Currently, for the conventional hot CRMA (HCRMA), there are two ways to introduce CR into the asphalt mixture (namely, wet process and dry process). In the wet process, CR is treated as a binder modifier. It is blended with asphalt binder to prepare AR first. Then, AR is mixed with aggregates and mineral fillers to prepare the AR mixture. In the dry process, CR is added into the aggregate gradation to replace part of the aggregates in asphalt mixture. Previous studies have documented the huge differences in mechanical performance and the workability of AR mixtures prepared by wet and dry processes. Similarly, the recycling method of CR affects the service performance of WCRMAs (Yu et al., 2020, 2017).

Given this, selecting an optimal recycling method is important for manufacturing asphalt mixture with the best overall engineering performance. This study aims to provide decision support for choosing the optimal method of recycling CR into wax-based WMA. This objective was separated into three sub-goals:

- Evaluating the influences of recycling methods on the overall performance of WCRMA.
- Grading the performance of WCRMAs.
- Determining the optimal recycling method.

In this study, asphalt mixture specimens with six different CR recycling methods were prepared in the laboratory. Experiments were performed on these specimens to evaluate the effect of recycling methods on the rutting resistance, moisture susceptible, rheological properties, fatigue resistance and workability of asphalt mixtures. Based on the experimental results, fuzzy logic was employed to quantitatively evaluate the performance grades of all the specimens. The weight matrix of all the properties was established using the Analytic Hierarchy Process (AHP) with the consideration of the environmental condition in southern China. The fuzzy comprehensive evaluation (FCE) method was used to assess the recycling methods. The optimal recycling method was obtained based on the laboratory and evaluation results.

2. Materials and sample preparation

2.1. Raw materials

One neat binder (PG 64–16), which is commonly used in southern China, was selected to prepare asphalt mixture. The sources of aggregate and mineral filler used to prepare asphalt mixture are basalt and diabase respectively. Stone matrix asphalt (SMA) mixture with the nominal maximum size of aggregate (NMSA) of 13.2 mm was chosen to prepare hot and warm CRMA. 4% was set as the designed air void of all the involved asphalt mixtures. 40 mesh crumb rubber was used in this study to manufacture AR mixtures. Sasobit, a commercial wax-based warm mix additive produced by the Fischer-Tropsch (FT) synthesis process, was adopted to prepare WCRMAs. More details on the raw materials utilized in this study were documented in previous publications (Leng et al., 2017; Yu et al., 2018b; Yu et al., 2020).

2.2. Recycling methods

To evaluate the effects of CR recycling methods on the performance of asphalt mixture, CRMAs were prepared with six recycling methods. As a reference, conventional HMAs were also prepared. The involved recycling methods are graphically presented by Fig. 1.

As shown in Fig. 1, six recycling methods were involved in this study, labeled from A to F. The corresponding asphalt mixtures are labeled as DM, WM, ARS + A, AR + S + A, ARSD + A, and ARSA, respectively. Asphalt mixture prepared with conventional hot mixing process was labeled as Ctrl.

In the hot mixing process, neat binder was mixed with aggregate at 160 °C. In method A, asphalt binder, aggregate, and CR were mixed together at 176 °C. In method B, AR was prepared firstly by adding CR into asphalt binder. The reaction condition was 60 min

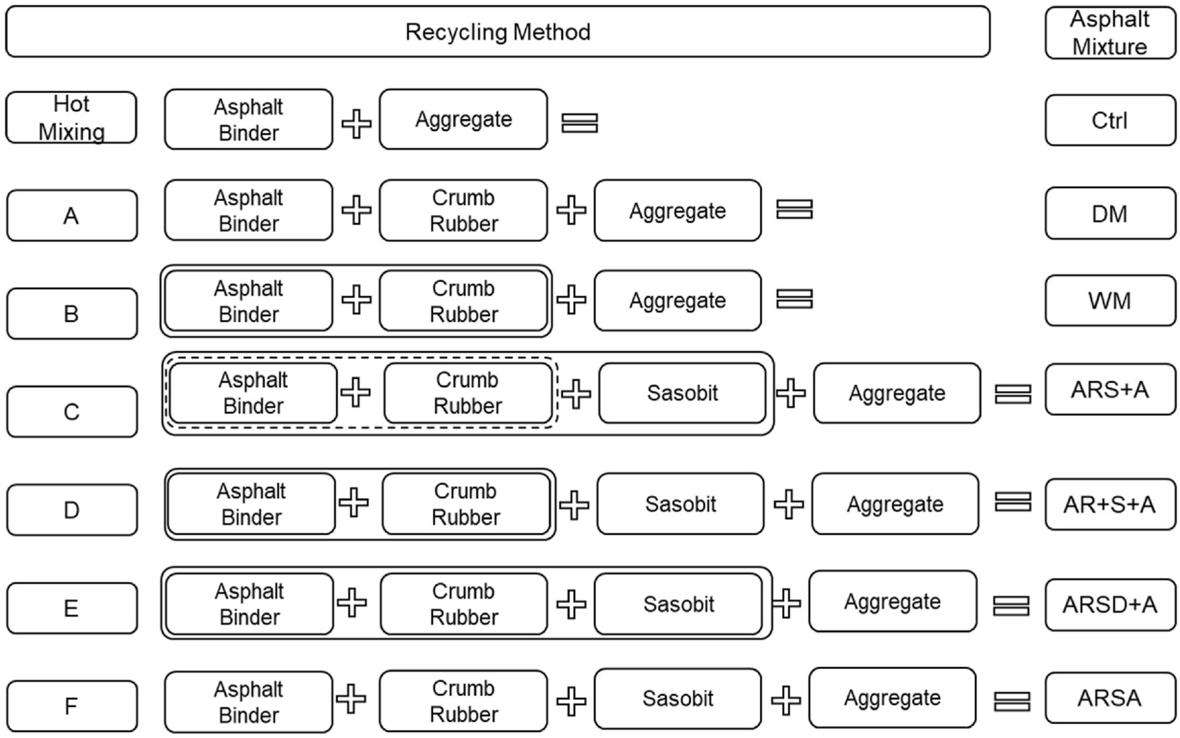


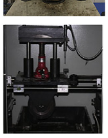
Fig. 1. Involved recycling methods.

(reaction time), 4000 rp/min (shearing speed), and 176 °C (reaction temperature). AR was then blended with aggregate at the same temperature to prepare asphalt mixture, WM. To prepare ARS + A, a wax-based warm mix additive (namely Sasobit) was mixed with prepared AR at 160 °C with a mixing time of 10 min followed by incorporating into aggregate. Asphalt mixture produced by directly mixing AR, Sasobit, and aggregate at 160 °C was labeled as AR + S + A. ARSD + A was prepared by blending asphalt binder, CR and Sasobit together (160 °C, 60 min) followed by mixing with aggregate at the same temperature. Recycling method F refers to mixing all the components together at 160 °C.

2.3. Sample preparation

Test samples were produced in accordance with the applicable standard guidance. The prepared samples, preparation guidance,

Table 1
Information about test samples.

Sample figure	Sample size	Preparation standard	Conducted test
	101.6 ± 0.2 mm in diameter 63.5 ± 1.3 mm in height	ASTM D6927-15 (ASTM International, 2015a)	Marshall stability and flow value test
	100 mm in diameter 60 ± 2.5 mm in height	ASTM D6925-15 (ASTM International, 2015b)	Workability evaluation
	100 mm in diameter 63.5 ± 1.3 mm in height	ASTM D4867-09 (ASTM International, 2014)	Moisture damage resistance test
	300 mm*300 mm*50 mm	BSI 598 part 110 (British Standard, 1998)	Rutting test
	380±6 mm in length 50±6 mm in height 63±6 mm in width	ASTM D7460-10 (ASTM International, 2010)	Fatigue test

and the corresponding tests are listed in Table 1. For each sample, three replicates were prepared.

3. Methodology

3.1. Experimental methods

To evaluate the effect of the recycling method on the performance of asphalt mixture, a set of laboratory tests were performed including Marshall stability and flow value test, workability test, moisture damage resistance test, rutting test, and fatigue test. These tests were selected as they are proven to reflect the service performance of pavement under traffic and environmental loading.

Marshall stability and flow value are important indicators for asphalt mixture design and evaluation. Marshall test was conducted in accordance with ASTM D6927-15 (ASTM International, 2015a).

The workability of asphalt mixture was characterized by compaction work that makes loose asphalt mixture dense. In this paper, cylinder samples were compacted using Superpave gyratory compactor (SGC). The more loading cycles to reach target height, the more compaction work was done by SGC, and therefore, the poorer workability the asphalt mixture has.

Indirect tensile strength ratio (ITSR), the ratio of the retained indirect tensile strength (ITS) of asphalt mixture over the ITS of asphalt mixture before freeze-thaw conditioning, was calculated as the indicator of moisture damage resistance. The freeze-thaw conditioning adopts a freeze-thaw cycle according to ASTM D4867 (ASTM International, 2014). The water-saturated cylindrical specimens were frozen at −18 °C for 6 °C hours followed by being immersed into a water bath at 25 °C for 24 h. The ITS of asphalt mixture before and after freeze-thaw conditioning are labeled as ITS-Dry and ITS-Soaked, respectively.

Rutting resistance, which is believed to be related to the high-performance of asphalt pavement, was investigated by loading wheel tracking (LWT) test in accordance with BSI 598 part 110 (British Standard, 1998). A constant loading (520 N) generated by a single rubber wheel was applied to the testing slab at 60 °C for 45 min. Responses of asphalt mixture (i.e., rutting depth and rutting rate) under the wheel loading were collected as the indicators of rutting resistance. Rutting depth refers to the permanent deformation of the sample caused by the wheel loading in comparison with the unloaded sample. Rutting rate is defined as the rate of rutting development from 30th to 45th minute.

In this study, four-point bending (4 PB) test was adopted to evaluate the fatigue resistance of asphalt mixture according to ASTM D7460 (ASTM International, 2010). The stiffness degradation of asphalt mixture under repeated loading was utilized as the metric of damage accumulation. Asphalt mixture reaches its fatigue life when the residual stiffness is reduced by 50% of the initial one. Fatigue response of the rectangle sample under five microstrain-controlled loadings (400, 600, 800, and 1000) was measured in this study. The test frequency and temperature were set as 10 Hz and 15 °C, respectively.

3.2. Fuzzy comprehensive evaluation

Fuzzy refers to these concepts that their boundaries are not clear, for instance, good, bad, high and low. Unfortunately, pavement engineers have to face these fuzzy concepts frequently. For instance, to decide on a paving material, pavement engineers have to quantitative the goodness of the materials. Fuzzy sets theory, proposed by Zadeh in 1965 (Zadeh, 1965), is a theory of graded concepts. In this theory, everything is a matter of grade. In other words, the truth value is not either completely true or completely false. Instead, the truth value varies between completely true, i.e. 1, and completely false, i.e. 0, both inclusive. In fuzzy mathematics, the degree to which an element belongs to a specific set is known as membership. Fuzzy comprehensive evaluation (FCE) method is a comprehensive evaluation method based on fuzzy mathematics which aims to comprehensively evaluate the membership of the objective to different grades. By means of FCE, fuzzy and qualitative problems can be converted to quantitative problems. There are mainly four steps to use the FCE method: determining the set of evaluation factors and the set of appraisal grades, setting the fuzzy mapping matrix, determining the weight vectors, and building a comprehensive evaluation vector.

A set of evaluation factors is a set consist of factors that are used to evaluate the objective. For an objective being evaluated by n indexes $(u_1, u_2, u_3, \cdots, u_i, \cdots, u_n)$, its set of evaluation factors is $U = (u_1, u_2, u_3, \cdots, u_i, \cdots, u_n)$. If there are m possible appraisal grades, namely, $v_1, v_2, v_3, \cdots, v_j, \cdots, v_m$, for each evaluation factor, the appraisal set can be expressed as $V = (v_1, v_2, v_3, \cdots, v_j, \cdots, v_m)$.

The membership matrix is built based on the membership of each evaluation factor to all the possible appraisal grades. Assume the membership of evaluation factor u_i is $r_i = (r_{i1}, r_{i2}, r_{i3} \cdots r_{im})$, the membership matrix $\boldsymbol{R}$ can be expressed as Eq. (1):

$$\boldsymbol{R} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \tag{1}$$

From this matrix, the membership of the evaluation factor u_i to the appraisal grade v_j is r_{ij}. The membership of each evaluation factor to appraisal grades is determined using membership functions. The typical curve forms of the membership function are triangular and trapezoidal curves. Fig. 2 shows the triangular curves of membership functions of an evaluation factor u_i to three possible appraisal grades (grade v_1 to grade v_3). In this figure, the criteria of three grades is a, b and c, respectively. The membership function, $\tilde{A}_{ij}(x)$, is derived as follows:

$$\tilde{A}_{i1}(x) = \begin{cases} 1 & x < a \\ (x-b)/(a-b) & a \le x \le b \\ 0 & b < x \end{cases} \tag{2}$$

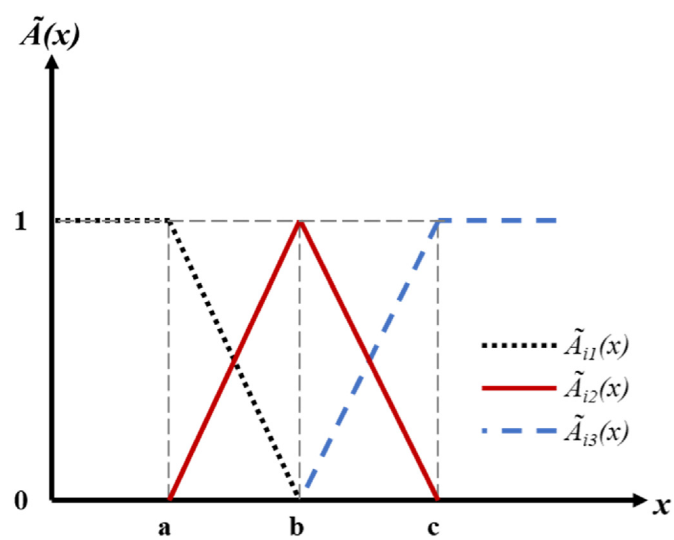


Fig. 2. Membership functions of index u_i.

$$\tilde{A}_{i2}(x) = \begin{cases} (x-a)/(b-a) & a \le x \le b \\ (x-c)/(b-c) & b \le x \le c \\ 0 & others \end{cases} \quad (3)$$

$$\tilde{A}_{i3}(x) = \begin{cases} 0 & x < b \\ (x-b)/(c-b) & b \le x \le c \\ 1 & c < x \end{cases} \quad (4)$$

The weight vector shows the weight or importance of each evaluation factor with respect to the evaluation of an object. Weight vector can be presented as $W = (w_1, w_2, w_3, \cdots, w_i, \cdots, w_n)$ with the boundary condition of $\sum_{i}^{n} w_i = 1$. From which, the importance of n evaluation factors is w_1, w_2, …, w_i, …, w_n, respectively. There are various methods to determine the weight vector. In this work, the analytic hierarchy process (AHP), was employed.

Fuzzy comprehensive evaluation vector is calculated from the weight vector and membership vector using fuzzy operators (Eq. (5)).

$$\boldsymbol{B} = \boldsymbol{W}^{\circ}\boldsymbol{R} \quad (5)$$

Where, $^{\circ}$ refers to the fuzzy operator, which is selected according to different purposes.

3.3. Analytic hierarchy process (AHP)

AHP method is a multicriteria decision-making approach providing a strong theoretical framework that allows precise quantitative calculation. The procedure of the AHP method mainly includes three steps: structuring the problem as a hierarchy, evaluating the hierarchy, and establishing priorities. More details on the AHP procedure can be found in one previous publication (Yu et al., 2020).

4. Experimental results

4.1. Marshall stability and flow value

Fig. 3 reveals the effect of CR recycling method on the Marshall stability and flow value of asphalt mixture. Obviously, asphalt mixtures containing CR exhibited higher Marshall stability than that without CR. This indicates the positive influence of CR on the high-temperature performance of asphalt mixture. Among these CR modified asphalt mixtures, Marshall stability and flow value vary depending on the recycling method. ARS + A and DW present the highest and lowest Marshall stability and flow value, respectively. The change of flow value reveals the effect of the recycling method on asphalt mixture's irrecoverable deformation at high temperature.

The variation of Marshall stability and flow value confirms the significant influence of the method of recycling CR on the performance of asphalt mixture. However, it should be noted that although the change of flow value was significant, flow value was not taken into consideration in FCE as it was not considered as a performance metric in the current technical specifications in China. Based on the value of Marshall stability, the recycling methods can be roughly ranked as C > B > D > E > F > A.

4.2. Workability

The volumetric properties, which are strongly affected by the workability, are fundamental to the service performance of asphalt mixture (Leng et al., 2018). During the construction process of asphalt pavement, loose asphalt mixture is manufactured in mixing plant and compacted by a roller. Workability is an index indicating the difficulty of mixing and compacting asphalt mixture. In comparison with asphalt mixture with better workability, the one with poorer workability is more difficult to be compacted. Higher air void contents than the designed value may lead to poorer bearing capacity. In this work, since the target height of specimens were set as same, the number of gyrations was adopted as the indicator of workability. For asphalt mixtures with the same compaction temperature, the larger the number of gyrations, the poorer the workability.

Fig. 4 illustrates the compaction temperature and the number of gyrations of all the involved asphalt mixtures. As can be seen, the workability of Ctrl was better than the warm mix asphalt mixtures containing CR. In addition, the recycling method of CR was found to affect the workability of asphalt mixture. DM presented the largest number of gyrations, i.e., the poorest workability. On the contrast, A + R + S + A had the best workability. Among all the asphalt mixtures, WM had the worst workability as it cannot be compacted at 145 °C. Instead, its compaction temperature was 15 °C higher than the others. In the further analysis procedure, WM's number of gyrations at 145 °C was assumed as 500.

The workability of recycling methods, considering both the compaction temperature and number of gyrations, can be ranked as B < A < E < D < C < F.

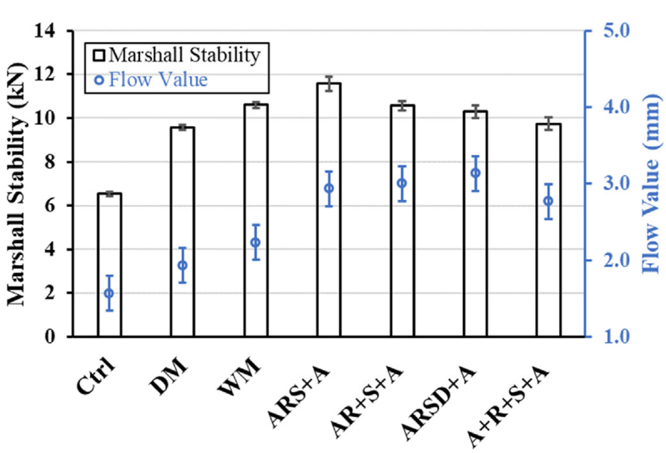


Fig. 3. Marshall stability and flow value of asphalt mixture.

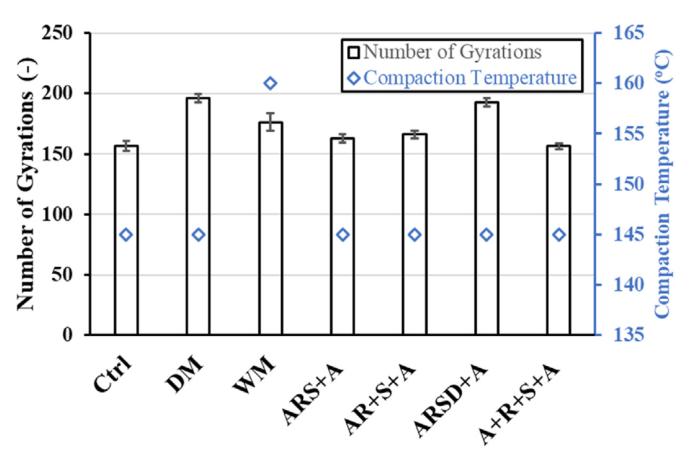


Fig. 4. Number of gyrations of asphalt mixtures.

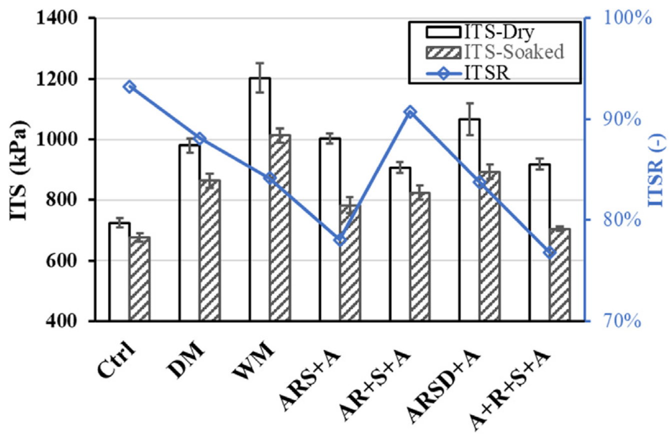


Fig. 5. Moisture resistance of asphalt mixtures.

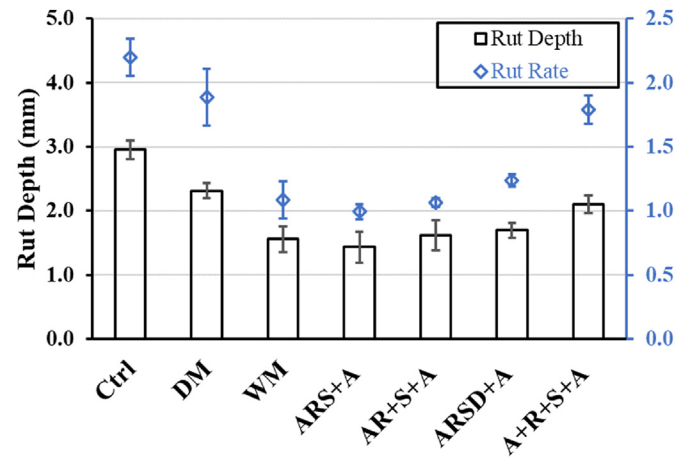


Fig. 6. LWT test results.

4.3. Moisture damage resistance

Asphalt mixture is a material having air voids inside through which moisture outside the asphalt mixture infiltrates into the asphalt mixture. These penetrated moistures swell and damage the internal structure of asphalt mixture due to the freeze-thaw cycle caused by temperature change (Xu et al., 2019). This damage process deteriorates the bearing capacity of asphalt mixture and leads to the propagation of the crack. ITSR is commonly used as an indicator of the moisture damage resistance property of asphalt mixture. Higher ITSR indicates superior moisture damage resistance. Fig. 5 presents the ITS and ITSR of asphalt mixtures.

As shown in this figure, the ITS of AR mixture was higher than that of Ctrl. This demonstrates the improvement effect of CR to the stiffness of asphalt mixture. However, the ITSR of all the asphalt mixtures containing CR was found to be lower than that of Ctrl, although the ITSR of all the asphalt mixtures far exceeds the minimum requirement value from the technical standard. This reflects the negative influence of CR on the moisture resistance of asphalt mixture. Among all the CRMAs, ITSR varied with the changing of CR recycling method. AR + S + A and A + R + S + A showed the highest and lowest ITSR, respectively. It is interesting to know that the gap between CRMA and conventional HMA in terms of moisture resistance can be filled by optimizing the recycling method of CR, as the ITSR of AR + S + A is close to it of Ctrl. Therefore, selecting a suitable CR recycling method could address the moisture damage concerns of CRMAs. Based on the asphalt mixtures' ITSRs, the ranking of the corresponding CR recycling methods, from high to low, is D > A > B > E > C > F.

It is interesting to mention that due to the limitation of the ITSR, it may not be the optimal indicator for evaluating the moisture damage resistance of modified asphalt mixture. The ITSR is defined as a ratio of indirect tensile strength with and without freeze-thaw conditioning. Therefore, the ITSR is a relative indicator which is only able to reveals the changes in the ITS of a specimen resulting from moisture damage ignoring the initial ITS of the specimen. In other words, for specimens with similar initial ITS, ITSR could be an effective metric for moisture damage resistance evaluation. Nevertheless, for samples with different initial strength, ITSR may not be a feasible indicator.

In this study, as shown in Fig. 5, asphalt mixture containing CR showed higher ITS than that of conventional HMA regardless of recycling method and freeze-thaw condition. This indicates the positive influence of CR on the moisture damage resistance. Among these CRMAs, WM presented the best moisture resistance performance because of its highest ITS after freeze-thaw conditioning.

In addition, it was found that the WCRMAs' ITS was lower than that of WM. This can be ascribed to the incompletely evaporation of moisture due to the lower production temperature of WCRMAs. The influence of Sasobit on the moisture damage resistance has been proven as insignificant by the previous study of the authors (Yu et al., 2018b).

4.4. Rutting resistance

Rutting mainly occurs in summer in the wheel paths. It is caused by the insufficient bearing capacity of asphalt mixture at high temperature. Rutting is one of the distresses that strongly affects the service performance of pavement as it destroys the evenness of pavement surface and fails the pavement structure. Therefore, rutting resistance is a very important property of asphalt mixture in a hot region. Fig. 6 illustrates the effects of CR recycling method on the rutting resistance of asphalt mixture. Higher rut depth reveals lower rutting resistance.

As expected, the rut depth of CRMAs was thinner than that of conventional HMA. Meanwhile, CRMAs' rut rate was lower than that of Ctrl. Based on the measured rut depth and rut rate, it can be concluded that the rutting resistance of CRMAs was better than that of Ctrl. This is majorly ascribed to the stiffness enhancement resulting from CR modification.

Apart from that, data presented in Fig. 6 indicated that the recycling method has a significant influence on the rutting resistance of CRMAs. ARS + A had the thinnest rut depth referring to the best rutting resistance followed by WM, AR + S + A, ARSD + A, A + R + S + A, and DM. Therefore, the ranking of the CR recycling method with respect to the rutting resistance performance, is C > B > D > E > F > A.

4.5. Fatigue resistance

After opening to traffic, asphalt mixture is exposed to traffic loadings. Asphalt mixture fails when the number of repeated loading exceeds its designed fatigue life. Fatigue resistance refers to the ability of asphalt mixture to withstand repeated loadings (Zhang and Oeser, 2020). The better the fatigue resistance, the longer the fatigue life. Fig. 7 shows the fatigue life of asphalt mixtures under different loading levels. These lines are also known as *N*–*S* curve of asphalt mixture, where, *N* refers to the number of loading cycles, *S* refers to strain. The position of *N*–*S* curve indicates the fatigue resistance of asphalt mixture. Asphalt mixture with *N*–*S* curve at a higher position has a longer fatigue life, and vice versa.

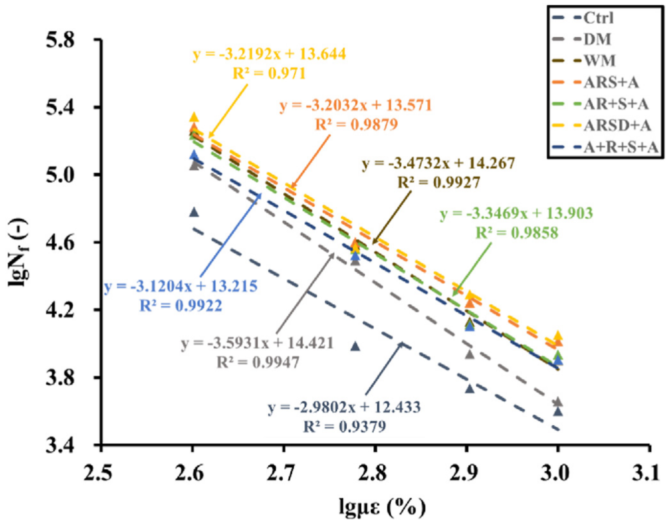


Fig. 7. Fatigue resistance of asphalt mixture.

The slope of the N–S curve terms to the sensitivity of asphalt mixture's fatigue resistance to the loading level, to be specific, the smaller the slope, the more sensitive to loading level.

As shown in Fig. 7, fatigue life of asphalt mixture changed as the changing of mixture type. Obviously, the fatigue resistance of Ctrl was much poorer than that of AR mixtures regardless of CR recycling method. This indicated the positive effect of CR in extending the fatigue life of asphalt mixture. By comparing the N–S curve of AR mixtures, it can be easily found that the CR recycling method plays a critical role in the fatigue resistance of asphalt mixture. Recycling method affected both the loading sensitivity and anti-fatigue property of asphalt mixtures. Among all the AR mixtures, ARSD + A had the best fatigue resistance performance, and the fatigue life of DM had the highest sensitivity to the strain levels.

To further quantify the differences in fatigue resistance of asphalt mixtures, the area under the N–S curve (labeled as F index) was collected from Fig. 7 and presented in Fig. 8. The definition of F index can be expressed by Eq. (6).

$$\boldsymbol{F} = \int_{\varepsilon_{min}}^{\varepsilon_{max}} \varepsilon \cdot N_f d\varepsilon \tag{6}$$

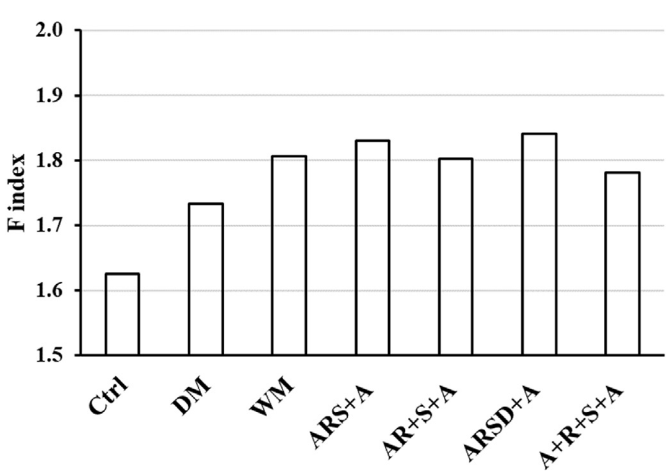


Fig. 8. F index of asphalt mixture.

Where ε_{min} and ε_{max} are the minimum and maximum strain (at logarithmic scale) involved in the fatigue test, respectively. N_f is the logarithmic value of fatigue life.

The advantage of using F index instead of the fatigue life is that the former takes into account both the loading sensitivity and fatigue life of asphalt mixture. A higher F index indicates better fatigue resistance. Obviously, CR recycling method E provides the best fatigue resistance performance followed by C, B, D, F and A.

5. Fuzzy comprehensive evaluation

5.1. Evaluation factors and appraisal grades

As discussed above, the effect of the recycling method on the performance of asphalt mixture was investigated from five perspectives, namely, Marshall stability and flow value, workability, moisture damage resistance, rutting resistance, and fatigue resistance. Therefore, the Marshall stability, number of gyrations, ITSR, rut depth, and fatigue index F were selected as evaluation factors. For each factor, five appraisal grades ($v1$: very poor, $v2$: poor, $v3$: middle, $v4$: good and $v5$: very good) were set. Fig. 9 shows the evaluation factor set and appraisal grade set involved in this study.

5.2. Fuzzy mapping matrix

Due to the different physical significance of the evaluation factors, the experimentally obtained evaluation values were processed before establishing a fuzzy mapping matrix. In this work, u_1, u_2, u_4, and u_5 were normalized. Table 2 lists the processed evaluation values.

Based on Table 2, the membership function of each evaluation factor was established. Fig. 10 presents the membership function of all the evaluation factors. In this figure, red solid line, blue square dot line, yellow double solid line, grey dash line and green long dah dot line refer to $v1$, $v2$, $v3$, $v4$, and $v5$, respectively.

According to Fig. 10, the membership of the evaluation factor to appraisals grade can be determined. For instance, u_1 of DM is 0.827. Membership function of u_1 is given as follows:

$$\tilde{A}_{11}(x) = \begin{cases} 1 & x < 0.83 \\ (x-0.87)/(0.83-0.87) & 0.83 \le x \le 0.87 \\ 0 & 0.87 < x \end{cases} \tag{7}$$

$$\tilde{A}_{12}(x) = \begin{cases} (x-0.83)/(0.87-0.83) & 0.83 \le x \le 0.87 \\ (x-0.8)/(0.7-0.8) & 0.87 \le x \le 0.91 \\ 0 & others \end{cases} \tag{8}$$

$$\tilde{A}_{13}(x) = \begin{cases} (x-0.7)/(0.8-0.7) & 0.87 \le x \le 0.91 \\ (x-0.9)/(0.8-0.9) & 0.91 \le x \le 0.95 \\ 0 & others \end{cases} \tag{9}$$

$$\tilde{A}_{14}(x) = \begin{cases} (x-0.87)/(0.91-0.87) & 0.91 \le x \le 0.95 \\ (x-1)/(0.95-1) & 0.95 \le x \le 1 \\ 0 & others \end{cases} \tag{10}$$

$$\tilde{A}_{15}(x) = \begin{cases} (x-0.95)/(1-0.95) & 0.95 \le x \le 1 \\ 0 & others \end{cases} \tag{11}$$

It is easy to obtain that $\tilde{A}_{12}(0.827) = \tilde{A}_{13}(0.827) = \tilde{A}_{14}(0.827) = \tilde{A}_{15}(0.827) = 0, \tilde{A}_{11}(0.827) = 1$. Therefore, the membership vector of u_1 for recycling method A is $(1, 0, 0, 0, 0)$.

Therefore, by repeating this process, the fuzzy mapping matrix of all the recycling methods can be obtained. Eq. (12) to Eq. (17) give the fuzzy mapping matrix of the recycling method A to F.

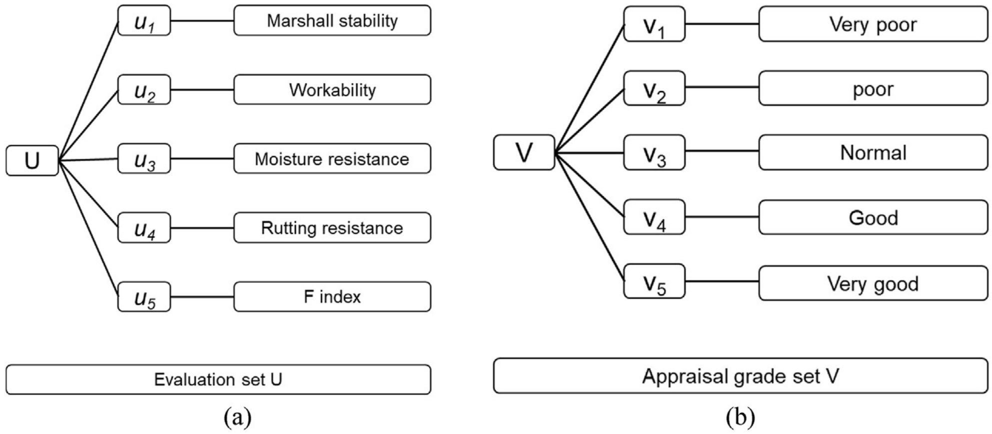


Fig. 9. Set of evaluation factors (a) and set of appraisal grades (b).

Table 2
Processed evaluation values.

	u_1	U_2	u_3	u_4	u_5
DM	0.827	0.392	0.881	0.783	0.942
WM	0.916	1.000	0.842	0.527	0.981
ARS + A	1.000	0.326	0.780	0.485	0.994
AR + S + A	0.914	0.332	0.908	0.547	0.979
ARSD + A	0.890	0.385	0.838	0.574	1.000
A + R + S + A	0.841	0.313	0.768	0.909	0.967

$$R_A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0.07 & 0.93 & 0 & 0 \\ 0 & 0 & 0.59 & 0.41 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.34 & 0.66 & 0 & 0 \end{bmatrix} \tag{12}$$

$$R_B = \begin{bmatrix} 0 & 0 & 0.84 & 0.16 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.11 & 0.89 & 0 & 0 \\ 0 & 0 & 0 & 0.53 & 0.47 \\ 0 & 0 & 0 & 0.76 & 0.24 \end{bmatrix} \tag{13}$$

$$R_C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.40 & 0.60 \\ 0 & 0.93 & 0.07 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.24 & 0.76 \end{bmatrix} \tag{14}$$

$$R_D = \begin{bmatrix} 0 & 0 & 0.91 & 0.09 & 0 \\ 0 & 0 & 0 & 0.55 & 0.45 \\ 0 & 0 & 0.23 & 0.77 & 0 \\ 0 & 0 & 0 & 0.79 & 0.21 \\ 0 & 0 & 0 & 0.85 & 0.15 \end{bmatrix} \tag{15}$$

$$R_E = \begin{bmatrix} 0 & 0.49 & 0.51 & 0 & 0 \\ 0 & 0 & 0.88 & 0.12 & 0 \\ 0 & 0.16 & 0.84 & 0 & 0 \\ 0 & 0 & 0.13 & 0.87 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

$$R_F = \begin{bmatrix} 0.71 & 0.29 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.07 & 0.93 \\ 0.10 & 0.90 & 0 & 0 & 0 \\ 0 & 0.89 & 0.11 & 0 & 0 \\ 0 & 0 & 0 & 0.32 & 0.68 \end{bmatrix} \tag{17}$$

5.3. Weight vector

The summer in southern China, for instance, Guangzhou, is longer than that of northern China. Therefore, in comparison with other properties, the high-temperature performance of asphalt mixture is more important in this region. In this work, according to the preliminary work, the importance of five evaluation factors is rutting resistance performance (ω_1) > fatigue performance (ω_2) > moisture damage resistance (ω_3) > Marshall stability (ω_4) > workability (ω_5). The pairwise comparison matrix of the evaluation factor is shown below (Yu et al., 2020):

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

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

$$\lambda_G = 5.1211$$

$$X_G = [0.7965,\ 0.5144,\ 0.2886,\ 0.1175,\ 0.0628]^T$$

After normalization, X_G can be rewritten as follows:

$$\omega_G = [0.4475, 0.2890, 0.1621, 0.0660, 0.0353\ ]^T$$

The consistency ratio of matrix G was 0.027 < 0.1, which verified the consistency of the pairwise comparison matrix. Therefore, the weight vector, W, is given below:

$$W = (w_1, w_2, w_3, w_4, w_5)^T = (0.0660, 0.0353, 0.1621, 0.4475, 0.2890)^T$$

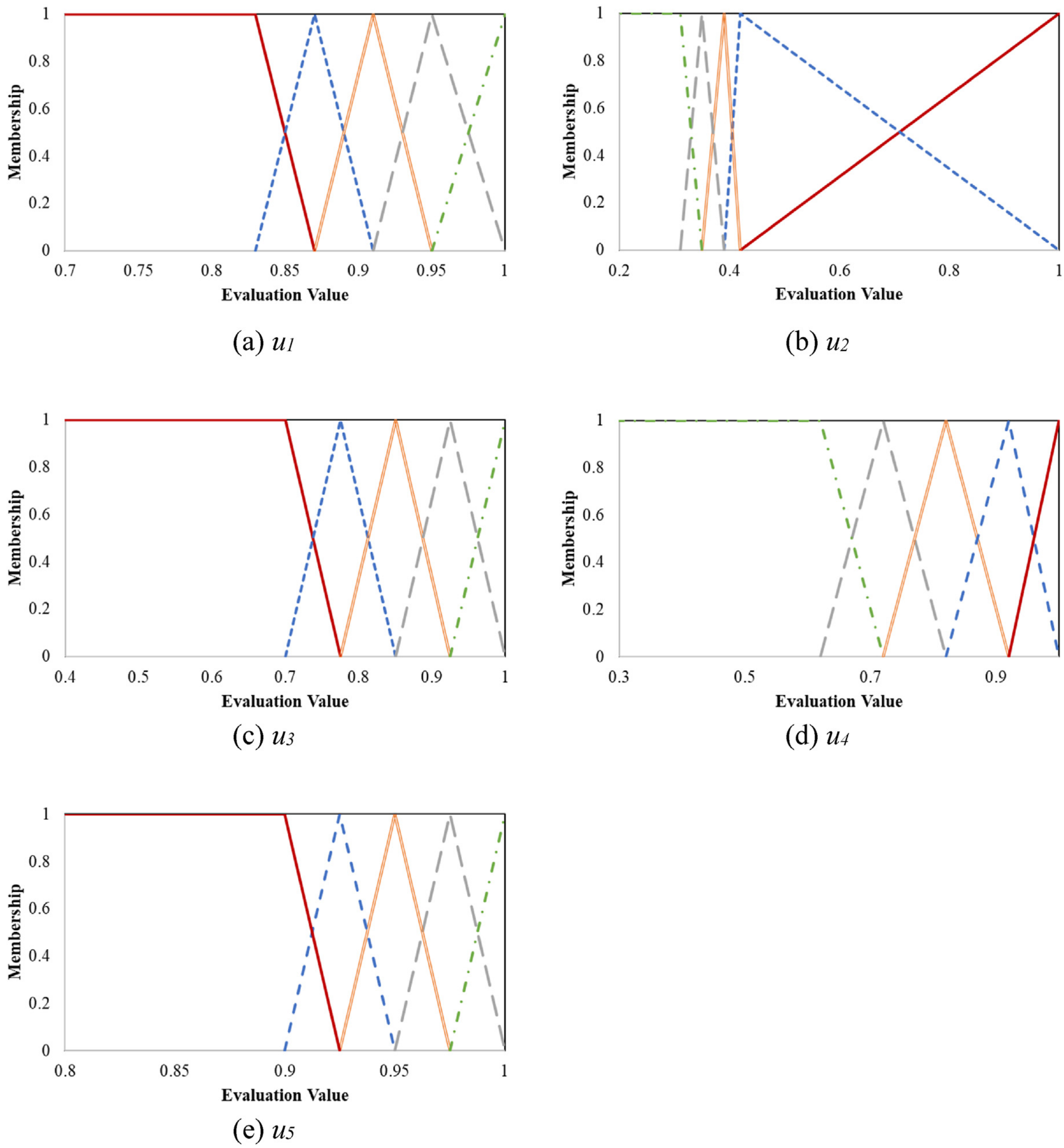


Fig. 10. Membership function of the evaluation factor.

5.4. Comprehensive evaluation vector

In this work, fuzzy operator $M(\cdot, \oplus)$ was employed to calculate the comprehensive evaluation vector as it is regarded to be able to make full use of all the information and weights (Zheng et al., 2019). The definition of $M(\cdot, \oplus)$ is given as follows:

$$\boldsymbol{B} = \boldsymbol{W}^{\circ}\boldsymbol{R} \tag{18}$$

Where,

$$^{\circ} = M(\cdot, \oplus) \tag{19}$$

$$\boldsymbol{B} = (b_1, b_2, b_3, \cdots, b_j, \cdots, b_m) \tag{20}$$

$$b_j = \sum_{i=1}^{n} w_i \cdot r_{ij} \tag{21}$$

The comprehensive evaluation vectors were then calculated and listed as below:

$$B_A = (0.514, 0.100, 0.320, 0.067, 0.000)$$

$$B_B = (0.035, 0.018, 0.200, 0.468, 0.279)$$

$$B_C = (0.000, 0.150, 0.012, 0.085, 0.753)$$

$$B_D = (0.000, 0.000, 0.097, 0.750, 0.153)$$

Table 3
Differences in rankings.

Recycling Method	Marshall Stability	Workability	Moisture Damage Resistance	Rutting Resistance	Fatigue Resistance	FCE
A						
B						
C						
D						
E						
F						

$$B_E = (0.000, 0.059, 0.261, 0.392, 0.289)$$

$$B_F = (0.063, 0.565, 0.048, 0.094, 0.231)$$

According to the comprehensive evaluation vectors, it can be concluded that recycling method C provides the optimal overall performance. To further determine the ranking of different recycling methods, each appraisal grade was given a specific score. The score for v_1 to v_5 is 1–5 with an interval of 1. Based on the comprehensive evaluation vectors, the final score of the recycling method can be calculated. The overall scores of recycling methods A to F, are 1.942, 3.938, 4.441, 4.056, 3.914, and 2.868, respectively. Since a higher overall score indicates a better overall performance, the ranking of six CR recycling methods is C, D, B, E, F, A. Table 3 compares the differences in the rankings obtained based on FCE and experimental results. Darker color refers to higher priority. As can be seen, ranking of recycling methods varies depending on the different properties obtained from laboratory. FCE comprehensively evaluated the overall performance of different recycling methods.

6. Summary and findings

This study presented an attempt for making decision on the optimal method of recycling crumb rubber derived from waste tire into wax-based WCRMA. Six possible recycling methods were taken into consideration in this work. Conventional HMA was employed as the reference group. Laboratory tests were performed to investigate the differences in the high-temperature performance, moisture resistance performance, fatigue resistance performance, workability and Marshall stability of asphalt mixtures resulting from various CR recycling methods. Fuzzy comprehensive evaluation method was used to determine the optimal CR recycling method with respect to the best overall engineering performance. The main findings of this work are summarized as follows:

- Crumb rubber shows positive influences on both rutting and fatigue resistance of asphalt mixture. However, it brings negative effects on the moisture damage resistance and workability of asphalt mixture.
- The incorporation of Sasobit improves the workability of hot mix CRMA significantly.
- Recycling method of CR has significant influences on the engineering performance of WCRMA.
- The optimal CR recycling method for hot and humid places (like southern China) is to prepare AR first followed by incorporating Sasobit to AR and finally blending the warm mix AR to aggregates.
- For the rainy regions, asphalt mixture produced by directly mixing AR, Sasobit, and aggregate at 160 °C may perform better because it showed the highest ITSR and ranked as second with respect to the overall performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Huayang Yu: Conceptualization, Resources, Writing - review & editing. **Yanlin Chen:** Data curation, Investigation, Writing - original draft. **Qi Wu:** Visualization, Investigation, Formal analysis. **Litian Zhang:** Data curation, Validation. **Zeyu Zhang:** Conceptualization, Methodology, Writing - original draft, Software. **Junhui Zhang:** Supervision, Funding acquisition. **Miomir Miljković:** Writing - review & editing. **Markus Oeser:** Supervision, Funding acquisition.

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