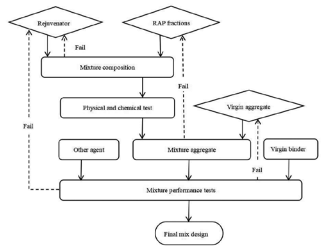
Mix ratio optimization design method for hot in-place recycled asphalt mixtures



Método de diseño de optimización de la proporción para mezclas asfálticas recicladas in situ en caliente

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RESUMEN

- El diseño de los componentes para el reciclado en caliente in situ (HIR) es la clave para determinar el rendimiento de la renovación de los pavimentos de asfalto. Sin embargo, los métodos de diseño existentes tienen numerosos problemas, como la gran demanda de tamaño de muestra y el descuido de la interacción de los diferentes factores y niveles. Con el fin de establecer un método de diseño de componentes razonable para las mezclas recicladas en caliente in situ, este estudio analizó el modo de acción del agente rejuvenecedor y optimizó el método de diseño de la mezcla mediante pruebas triaxiales. Se analizó el mecanismo de regeneración del agente rejuvenecedor en el pavimento de asfalto recuperado (RAP) y se determinaron inicialmente las condiciones de trabajo óptimas del agente rejuvenecedor mediante pruebas de rendimiento físico, composición química y ensayos reológicos de cizallamiento dinámico. Además, se analizaron las influencias del agente rejuvenecedor, del RAP y del nuevo pavimento asfáltico a altas y bajas temperaturas y la estabilidad al agua de la mezcla de asfalto reciclado, con pruebas que utilizaban un método de diseño triaxial que combinaba pruebas reológicas de deformaciones permanentes, pruebas reológicas de flexión trabecular y pruebas de disgregación por congelación-descongelación. El diseño óptimo de la mezcla reciclada se determinó sobre esta base. De acuerdo con los resultados de las pruebas, el agente rejuvenecedor y el RAP pueden influir en el rendimiento del pavimento de la mezcla reciclada más que el asfalto nuevo. Cuando la dosis del agente rejuvenecedor es del 5% de la masa total de asfalto, la proporción de RAP y asfalto nuevo es del 80% y 20% de la mezcla, respectivamente, el efecto del reciclado es el mejor. El método propuesto es económico y respetuoso del medio ambiente y se ha aplicado bien en el mantenimiento de la red principal de carreteras en la ciudad de Hanzhong, provincia de Shaanxi, China, desde 2017. Los resultados de la investigación pueden servir de referencia para la ingeniería de HIR.
- **Palabras clave:** HIR, Dosis de renovador, RAP, Ensayo reológico de cizallamiento dinámico, Método ortogonal.

ABSTRACT

The design of components for hot in-place recycling (HIR) is the key to determining the performance of asphalt pavement regeneration. However, existing design methods have numerous problems, such as the large demand for sample size, and the neglect of the interaction of different factors and levels. In order to establish a reasonable component design method for hot in-place recycled mixtures, this study analyzed the action mode of the rejuvenator and optimized the mix design method using orthogonal tests. The regeneration mechanism of the rejuvenator in the reclaimed asphalt pavement (RAP) was analyzed and the optimum working conditions of the rejuvenator were determined initially by means of physical performance, chemical composition and dynamic shear rheological tests. In addition, the influences of rejuvenator, RAP and new asphalt at high and low temperatures and the water stability of the recycled asphalt mix were analyzed, with testing using an orthogonal design method combining rheological tests for wheel rutting, trabecular bending rheological and freeze-thaw splitting tests, the optimum design of the recycled mixture was determined on this basis. According to the test results, the rejuvenator and RAP can influence the pavement performance of the recycled mixture more than new asphalt. When the rejuvenator dose is 5% of the total asphalt mass, the ratio of RAP and new asphalt is 80% and 0% of the mixture, respectively, the recycling effect is the best. The proposed method is economical and environmentally friendly and has been well applied in ordinary trunk road maintenance engineering in Hanzhong City, Shaanxi Province, China, since 2017. The research findings can provide references for HIR engineering.

Keywords: HIR, Rejuvenator dose, RAP, Dynamic shear rheological test, Orthogonal method.

1. INTRODUCTION

Financial pressure in the road department sharply increased with the number of roads that shift from the construction phase to the maintenance phase and the rise in the costs of petroleum asphalt and aggregates. Hot in-place recycling (HIR) is developed under this circumstance. It is a regeneration technology with minimal CO_2 emission [1] and solves the disadvantages of traditional regeneration techniques, including the low utilization of recycled materials and high transportation cost. Given its high economic efficiency and environmental protection, HIR has promising application prospects in pavement repair projects. However, seldom efforts have been devoted to the improvement of the mix design method. HIR is the regeneration technology with the highest recycling utilization. The proportion of reclaimed asphalt pavement (RAP) reaches as high as 90% [2]. The unreasonable mix design of asphalt mixture causes fatigue cracking and poor interlayer contact of the recycled pavement frequently. Therefore, optimizing the mix design method of recycled mixtures is vital for the promotion of HIR technology.

Hot in-place recycled mixtures are generally composed of RAP, rejuvenator, new asphalt, mineral powder, and aggregates. Some scholars in the world have been searching for a reasonable design method of asphalt pavement mixtures. Several design methods, such as the superpave mix design method [3], Marshall mix design method [4], Bailey method [5], and GTM method [6], have been proposed. These methods have been applied in HIR projects and have achieved satisfactory results. Nevertheless, these methods encounter challenges in the mixing ratio design of mixtures. All of the aforementioned methods control different influencing factors, including rejuvenator, RAP, and new asphalt as a single variable. However, the influences of the interaction among these influencing factors on the performance of the mixture are neglected, thereby resulting in low assessment accuracy. Moreover, some contradictions among the performance of hot in-placed recycled mixtures exist because of the interaction of complicated conditions. Thus, placing all the influencing factors on the same level to design the mixing ratio will complicate workloads, hinder balancing requirements for comprehensive pavement performance, and affect the quality of recycled asphalt pavement directly, which have not been considered.

Giving comprehensive consideration to the influence mechanism of rejuvenator, taking into account the interaction of different parameters on the pavement performance, a new mix design method for hot in-placed recycled mixtures was proposed on the basis of an orthogonal test in this paper.

2. STATE OF THE ART

HIR technology has important advantages. It is also preferred in large pavement repair projects. So far, scholars have explored the development of HIR technology from different perspectives and optimized the design scheme of hot recycled mixtures on the basis of performance tests and comprehensive mixing. These studies mainly concentrated on performance tests under single control condition of influencing factors. For example, Noferini et al. [7] analyzed the influences of RAP on the pavement performance of recycled asphalt mixtures and found a threshold for RAP dosage. Excessive RAP can improve the physical and rheological properties of asphalt slightly. He et al. [8] analyzed the influences of RAP dosage on the pavement performance via the freeze-thaw splitting, wheel rutting, and trabecular bending rheological tests. Their results demonstrated that RAP could improve the high-temperature stability of recycled asphalt mixtures but might decrease low-temperature cracking resistance. Wang et al. [9] mixed rejuvenator into aged asphalt at different proportions and discussed the influences of rejuvenator on the basic physical and rheological performance of aged asphalt. They pointed out that rejuvenator could improve the workable performance and low-temperature cracking resistance of recycled asphalt drastically but would reduce the high-temperature stability of recycled asphalt. Ali et al. [10-11] tested the performance of recycled mixtures by using a Hamburg wheel tracking device and an indirect tensile experiment, assessed the cracking, rutting, and flooding resistances of recycled mixtures. They proved that the service life of recycled asphalt pavement could reach 7-14 years. Bouraima et al. [12] tested the physical properties of an asphalt mixture through a multistress creep recovery test and a trabecular bending rheological test. They carried out a comparative analysis on main performance changes of recycled asphalt mixtures between two lanes during HIR process and proved the influences of loading conditions on the changes in the performance of different lanes. Qi et al. [13] explored the influencing factors of the freeze-thaw splitting intensity ratio and the residual stability of recycled mixtures throughout hot recycling. They proved that the freeze-thaw splitting test is superior to the immersion Marshall test. These studies all laid the foundations for designing a performance test for hot in-place recycled mixtures. However, they selected single influencing factors in the mix design and neglected the effects of the interactions of different factors on recycled pavement performance.

Tran et al. [14] determined the best rejuvenator dosage for RAP to recover pavement performance through a rheological test to develop a design scheme applicable for hot recycled mixtures. Meanwhile, they mixed RAP with new aggregates at the proportion of 20% and 50%. They determined the optimal mixing ratio of asphalt mixtures using comparative analysis. West et al. [15] extracted asphalts from RAP from different regions of USA and mixed the extracts with new aggregates after recycling to eliminate the influences of contingency. They prepared 30 mixtures with different mixing ratios, and RAP content ranged within 25% and 55%. The optimal mixing ratio was further determined through a series of performance tests. Research results demonstrated that this design method can yield a hot mix asphalt mixture that meets the regeneration requirements. These studies set up the design steps of rejuvenator and RAP in hot recycled asphalt mixtures systematically. These studies provide an idea for the experimental design of the mixing ratio for hot in-place recycled mixtures. However, the mixing ratio design of asphalt mixtures involves numerous influencing factors. It requires a large sample size for the design based on the above procedures. Moreover, these design methods are applicable in situations when the RAP proportion is less than 55%. Given the high RAP dosage of hot in-place recycled mixtures, the mechanical properties and microstructures of the mixtures vary from those of asphalt mixtures obtained through other recycling methods. Therefore, the design scheme of hot in-place recycled mixtures must be adjusted according to their RAP content.

Relevant researchers have proposed the concept of applying RAP in recycled pavement completely to save costs. For example, Zaumanis et al. [16-17] discussed the influences of 11 rejuvenators on RAP performance. A design method to determine rejuvenator content was determined on the basis of rheology and micromechanics. Moreover, the performance records of RAP were analyzed, and a design method for adjusting the performance of mixtures by changing the RAP source, adjusting the fine powder content of the mixture, and finally adding new asphalt was proposed. They concluded that given sufficient mixing ratio design conditions, the performance of recycled asphalt mixtures with 100% RAP is basically the same as that of conventional ones. Although this design method increases the utilization of RAP, recycled asphalt mixtures easily suffers brittle failure, and its resistance to fatigue cracking declines dramatically because of low oil content. To achieve the standard performance of RAP, excess rejuvenators must be used. Although rejuvenators can increase the quality of RAP in the short run, this improvement is limited, and the probability of pavement cracking and rutting will increase considerably in the long run. Pavement quality is not guaranteed. Therefore, RAP performance must be evaluated comprehensively, and its optimal dosage must be determined reasonably.

To increase automatic weighing accuracy, Sivilevičius et al. [18] proposed a mixing ratio design formula based on mixture uniformity and calculated the optimal RAP dosage through the general allowable deviation method according to the properties of RAP and the type of recycled hot mixtures. This design method was applied in plant hot-mix recycling and HIR technologies. The accuracy of RAP dosage reached the tolerance of mean composition (±1.5%) regulated by ASTM D995-95b. Zhou et al. [19] discussed the specific mode of action of rejuvenator on aged asphalt and constructed a mathematical model of recycled asphalt composition and rejuvenator dosage. They found that the correlation coefficient between recycled asphalt composition and rejuvenator dosage exceeded 0.98. Makowska et al. [20] investigated the relationship of rejuvenator dosage with the cross-sectional area and volume of rutting during HIR and suggested the calibration of complex viscosity based on apparent Newtonian viscosity through the correction factor derived from the phase angle. Thus, rheological performance was optimized, and the combined algorithm for optimal mixing ratio between new and recycled materials and rejuvenator was determined. These studies avoided the influences of external factors on automatic weighing accuracy by constructing the mathematical models of the dosage of hot in-place recycled materiels. However, different aggregates interact during recycling. Guaranteeing the long-term performance of recyced pavement and determining the dosage of rejuvenator or RAP directly remain difficult if only uniformity, ingredient content, or volume coefficient are considered, whereas the influences of subsequently adding materials on the performance of the mixture are neglected, and the experimental verification of pavement performance remains insufficient.

Yu et al. [21] collected field data before and after the implementation of HIR to describe the long-term performance of HIR sections. They also emphasized the advantages by HIR, including less energy and material consumption, avoidance of long-distance transportation, and has lower cost than hot mix asphalt pavement. Makowska et al. [22] investigated the life cycle of HIR projects and reported that this type of recycling has been the major pavement preservation technology used in high-volume roads in Finland, currently constituting 50% of all road construction expenditures. Quresh et al. [23] conducted a comparative evaluation of the selected pavement sections before and after the implementation of HIR, proposed that lower mix temperature and insufficient compaction would lead to lower in-place air voids of recycled wearing course, and affect the quality of regeneration projects. These studies prove the necessity of improving this method from the side.

To solve existing study shortages, a new mix design method for hot in-place recycled mixtures based on the orthogonal test was proposed in the present study. Specifically, the mode of action of the rejuvenator was analyzed, and the dosage of the rejuvenator was determined initially by combining the physical property, the chemical component, and the dynamic shearing rheological tests. On this basis, orthogonal test results under different dosages of the rejuvenator, RAP, and new asphalt were analyzed via the rutting, the trabecular bending rheological, and the freeze-thaw splitting tests. The optimal mixing ratio of the recycled mixture was determined on the basis of the analysis results.

The remainder of this work is organized as follows. Section 3 introduces the general content of the test and the orthogonal test design method. Section 4 analyzes the action mechanism of the rejuvenator and the orthogonal test results of pavement performance of the mixture. Section 5 discusses the economic and environmental benefits of the proposed method. Section 6 provides the conclusions.

3. METHODOLOGY

3.1. TEST FLOW AND PREPARATION

The test design in this study mainly includes two parts, namely, the binder test and the pavement performance test based on the orthogonal method. The test flow is shown in Fig. 1.

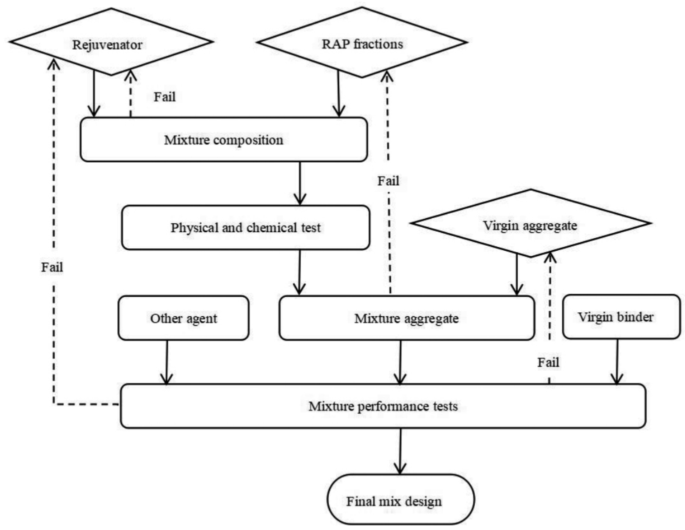

Fig. 1: Test process

The rejuvenator type was RA-F0110 from China, it is an oily liquid with a chemical composition similar to that of asphalt. The type of new asphalt was Kelian 70-A from China. RAP was collected from pavement surfaces, which were milled at a depth of 5cm in the HIR project. The aged asphalt was extracted and purified from RAP using toluene as a solvent according to ASTM D2172 [24], and recovered using a rotary evaporator [16], according to ASTM D5404 [25]. The basic parameters and regulated values of the rejuvenator and the asphalts are listed in Tables I and II (see section: supplementary material) in accordance with Chinese standard JTG E20-2011 (hereinafter referred to as the standard) [26]. The new asphalt mixture was graded AC-13. Coarse and fine aggregates were collected from a quarry in China. The grading of the new and recycled asphalt mixtures is shown in Fig. 2 (see section: supplementary material).

3.2. BINDER TEST

3.2.1 Physical and chemical tests

The penetration (25 °C), ductility (5 °C), softening point, and viscosity (135 °C) of the asphalt binders were tested in accordance to the standard. The requirements for the properties of recycled asphalt are presented as follows: the 25 °C needle penetration should be between 60–80 mm, the softening point should be higher than 46 °C, and ductility at 15 °C should exceed 100 cm.

The content changes before and after asphalt aging were measured by an asphalt component detector [27]. The relationship between the chemical composition and physical properties of asphalt can be established, and the preliminary dosage of the rejuvenator can be determined through physical and chemical tests.

3.2.2 Dynamic shear rheological test

The device, which is composed of a loading device and a data acquisition system, is shown in Fig. 3 (see section: supplementary material). The loading device applied sine oscillating loads on specimens at a frequency of 10 rad·s^{-1}, and the strain value (γ)

Test schemes	Factor levels			Specific parameters		
	A	B	C	A (%)	B (%)	C (%)
1	1	1	1	4	60	0
2	1	2	2	4	70	0.2
3	1	3	3	4	80	0.4
4	2	1	2	5	60	0.2
5	2	2	3	5	70	0.4
6	2	3	1	5	80	0
7	3	1	3	6	60	0.4
8	3	2	1	6	70	0
9	3	3	2	6	80	0.2

Tabla IV . Orthogonal test schemes

was 12%. The control and data acquisition system was used to record temperature, complex shear modulus *G**, and phase angle *δ*. The rutting factor *G*/sin(δ)* and the fatigue factor *G*•sin(δ)* were also calculated. The diameter and height of the asphalt specimens were set as 25mm and 1 mm, respectively. The temperatures were set at 50 °C, 60 °C, 65 °C and 70 °C.

3.3. MIXTURE TEST

3.3.1 Wheel rutting test

The wheel rutting test was used to assess the high-temperature performance of the recycled mixture under dry conditions following the standard. In this study, the dimensions of the specimens were 300 mm × 300 mm × 50 mm (l × w × h). Prior to the test, the specimens were maintained in the test device at 60 °C, and a repeated loading of 0.7 MPa was applied on the mixtures at a wheel speed of 42 passes per min. The rutting depth of the specimens during the test was recorded to calculate the dynamic stability.

3.3.2 Trabecular bending rheological test

The trabecular bending rheological test was conducted according to the specification, which is generally used to measure the low-temperature parameters of asphalt mixtures. The specimens were set at 300 mm × 300 mm × 50 mm. In the test procedure, a load of 50 mm per min was applied on the specimen, and failure strain was measured at −12 °C. Three replicates were performed for each condition, and the mean value was considered.

3.3.3 Freeze-thaw splitting test

The freeze-thaw splitting test was used to assess the water stability of the recycled mixture. The diameter and height of the specimens were 111.6 mm and 63.5 mm, respectively. The specimens were stored sequentially in water at −18 °C, 60 °C, and 25 °C for 16, 24, and 2 h, respectively. Then, the freeze-thaw splitting strength ratio were obtained at a speed of 50 mm/min.

3.4. ORTHOGONAL DESIGN METHOD OF PAVEMENT PERFORMANCE

An orthogonal design method [28] was applied in the mix ratio design. The ratio of rejuvenator (A), RAP (B), and asphalt (C) were selected as influencing factors, whereas high and low temperature performance and water stability were chosen as three levels. The values of A were recorded as A_1, A_2, and A_3. The values of B and C were recorded in the same manner. L_9 (3^4) orthogonal test table was applied as shown in Table III (see section: supplementary material), and nine groups of specimens were manufactured on the basis of the combinations in Table IV. The performance of the specimens under different factors and level conditions were analyzed through rutting, trabecular bending rheological, and freeze-thaw splitting tests, respectively. Test results are shown in Table V (see section: supplementary material). The influences of different factors on pavement performance have been discussed through range and variance analysis, and the variance analyses were conducted by using SPSS software.

4. TEST RESULTS AND ANALYSIS

4.1. EFFECTS OF THE REJUVENATOR ON ASPHALT RECYCLING

4.1.1 Physical property test

In Fig. 4, when rejuvenator dosage is zero, the needle penetration and ductility of the recycled asphalt deviate from standards drastically, but the softening point is slightly higher than the standards. These results are manifested by asphalt hardening, low plasticity, and good thermal resistance. With the addition of the rejuvenator, needle penetration and ductility decline gradually, whereas softening point and viscosity increase. The performance is improved gradually to the standard value. When the dosage of the rejuvenator is 4% of the total asphalt mass, the softening point meets the standards, whereas needle penetration and ductility are slightly lower (8% and 25%) than the standards. When the dosage of the rejuvenator is 5% of the total asphalt mass, the needle penetration increases by 150%, and ductility increases by 648% to 143 mm, whereas the softening point declines to 48.6 °C, all

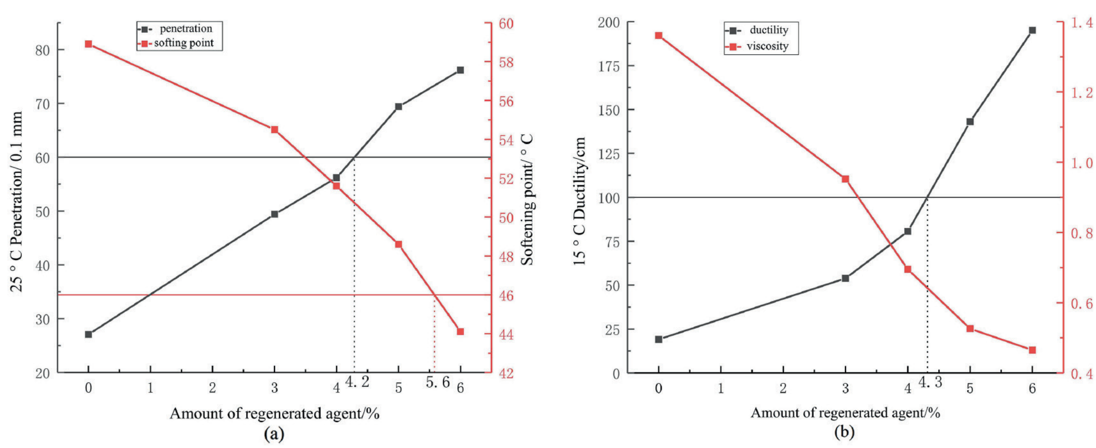

Fig. 4: Influences of the rejuvenator of recycled asphalt. (a) The ductility and viscosity (b) The needle penetration and softening point

Components	Rejuvenator	70-A asphalt		Dosage of rejuvenator (%)			
		Matrix asphalt	Aged asphalt	5	10	15	20
Saturation component(%)	23.21	11.61	12.11	11.92	11.78	11.72	11.70
Aromatic component(%)	44.63	30.73	27.93	28.82	29.22	29.92	30.74
Colloid(%)	24.17	38.14	31.92	32.65	33.51	34.39	35.22
Asphaltene(%)	7.99	19.52	28.04	26.61	25.49	23.97	22.36

Table VI . Changes of composition before and after asphalt aging

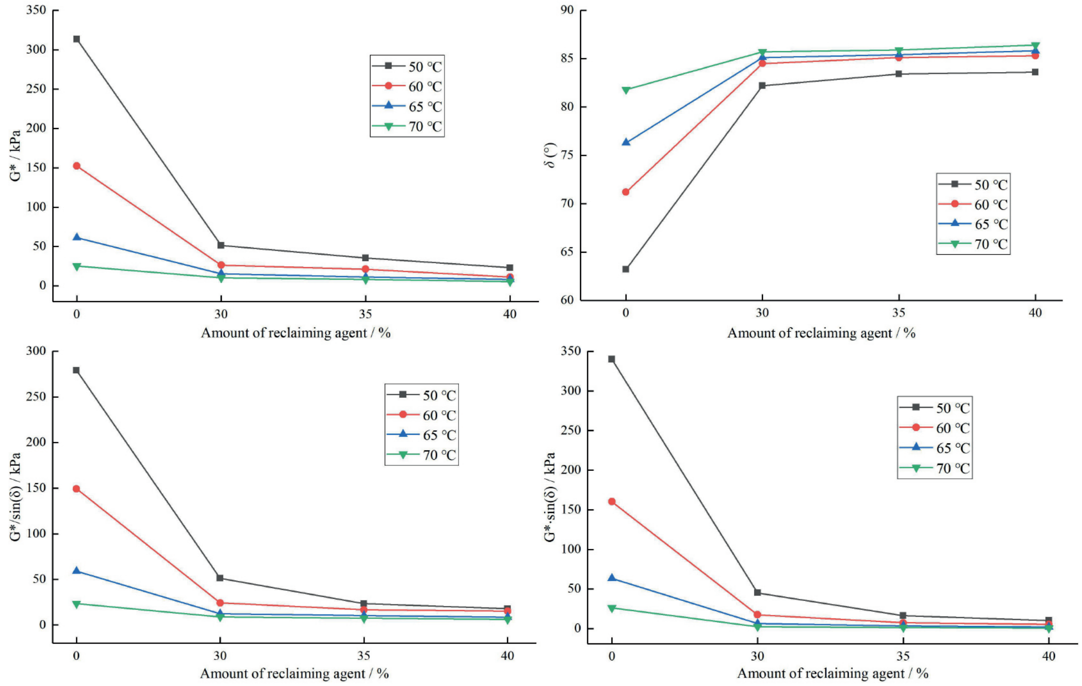

Fig. 5. DSR test results obtained under different rejuvenator dosages

three indexes meet the standards. Based on the intersection of the optimal dosage of three indexes in figures, the dosage of the rejuvenator is determined initially to be between 4.3% and 5.6%. According to the variation trend shown by the above broken line, some correlations exist among different indexes. the viscosity of asphalt has an evident linear relationship with other three indexes. It is positively correlated with needle penetration and ductility but is negatively correlated with softening point.

4.1.2 Chemical composition test

Ultraviolet irradiation and heavy-duty fatigue damages will cause asphalt aging. The volatilization, polymerization, and dehydrogenation of the light oil content changed the four components of asphalt. As shown in Table VI, the contents of saturation components and asphaltene have increased slightly, whereas those of aromatics and colloids have decreased, the aged asphalt shows a gel state. With the increase in the dosage of the rejuvenator, the composition of aged asphalt is improved and gradually approaches matrix asphalt. The analysis of test data reveals that the compositional changes of asphalt witness certain degree of transfer rather than simple superposition likely because the rejuvenator that has penetrated the aged hard asphalt can disperse and dissolve asphaltene. Therefore, the asphalt becomes soft with the addition of a rejuvenator, resulting in an increase in needle penetration and ductility, and decreasing softening point, the resistance of the recycled pavement to fatigue cracking is increased.

In contrast to that in other recycling methods, the hot in-place recycled mixture is heated fully, the clustering mixture is softened, the penetration path of rejuvenator is shortened, and the action of rejuvenator is more uniform and thorough. These are some reasons for the high utilization of RAP during HIR process. However, merging the rejuvenator completely still requires a certain time because of the serious hardening of the asphalt. Thus, the dose of the rejuvenator should be reduced appropriately according to experience.

4.1.3 DSR test

G^* is the measurement of the total resistance of materials under repetitive shearing deformation, and δ is the viscosity performance shown by materials during loading, which is the hysteretic angle between the generated sine strain and the sine stress applied by the instrument. The elasticity and viscosity of asphalt mixtures could be characterized by G^* and δ, respectively. $G^*/sin(\delta)$ is defined as the rutting factor. High values of $G^*/sin(\delta)$ are associated with the high elasticity of the asphalt mixture and good high-temperature performance. The fatigue factor $G^*/sin(\delta)$ reflects the fatigue resistance of asphalt at room temperature. A high fatigue value indicates poor fatigue resistance. SHRP indicates that $G^* \bullet sin(\delta) \leq 5000Kpa$. If the temperature is considerably less than the critical temperature, then the temperature range for the occurrence of the fatigue damages of asphalt pavement is reduced, and the fatigue performance of the mixture is improved.

Fig. 5 shows that the phase angle declines after asphalt aging, whereas the complex shearing modules and rutting factor increase. The elasticity of asphalt becomes prominent. With the addition of the rejuvenator, the phase angle increases under different temperatures, whereas G^*, $G^*/sin(\delta)$ and $G^*\bullet sin(\delta)$ decline. The asphalt is softened, and viscosity is enhanced. With the increase in rejuvenator dosage and temperature, the rutting factor of asphalt declines gradually, indicating deteriorating high-temperature performance. The fatigue factor of the asphalt declines with the increase in rejuvenator dosage. The fatigue strength of asphalt always meets the requirements before and after the addition of the rejuvenator. In a word, the rejuvenator can improve resistance to fatigue deformation and the cracking behavior of aged asphalt dramatically. Moreover, such improvement is prominent under low temperatures.

The rejuvenator dosage has a threshold. When the rejuvenator dosage is less than 30%, the rejuvenator can improve the performance of aged asphalt effectively. On this basis, the change amplitude tends to be gentle with the increase in rejuvenator dosage. In practical applications, the rejuvenator dosage should be controlled to less than 30% for the full use of the rejuvenator.

By using chemical and dynamic shear rheological test, the regeneration mechanism of rejuvenator in aged asphalt was analyzed. These tests can provide references to select the type and dosage of the rejuvenator. However, comparing with the physical properties, these tests seem less valuable and still can be simplified appropriately in subsequent engineering applications. Based on the discussions above, the preliminary dosage of the rejuvenator is between 4% and 6%.

4.2. ANALYSIS OF THE ORTHOGONAL TEST RESULTS OF MIXTURE

4.2.1 Range analysis

Test data were processed by range analysis. The range analysis in Tables VII, VIII, and IX (see section: supplementary material) were obtained. In these tables, K_{ij} (i = 1, 2, ...,3; j = 1, 2, ..., 3) are the mean test results of evaluation index i under the level j. R_f refers to range, and a high value of R_f reflects the large influences of the factor on the index.

The data in Table VII show that the priority pattern of factors that influence high-temperature stability of hot in-place recycled mixtures is rejuvenator > RAP > new asphalt. Among them, the rejuvenator is the primary influencing factor of the high-temperature performance of the recycled mixture. According to the data in Table VIII, the priority pattern of factors that influence low-temperature resistance to the cracking of the hot in-place recycled mixture is rejuvenator > new asphalt > RAP, where the rejuvenator is the main influencing factor. In Table IX, the priority pattern of factors that influence water stability of hot in-place recycled mixture is RAP > rejuvenator > new asphalt, in which RAP is the primary influencing factor. To summarize, the rejuvenator and RAP improve the high and low temperature performance and water stability of the recycled mixture more effectively than new asphalt.

4.2.2 Variance analysis

To analyze the influencing degrees of the dosage of the rejuvenator, RAP, and new asphalt on the pavement performance of recycled asphalt mixtures, the F values of the three factors under different pavement performance indexes were calculated on the basis of the variance analysis of main effect, thereby enabling the judging of the significance of the influences of factors. The significance levels of different factors were evaluated on the basis of $F_{0.01}(n_1, n_2)$, $F_{0.05}(n_1, n_2)$, and $F_{0.01}(n_1, n_2)$, where n_1 and n_2 are the degree of freedom (DOF) of influencing factors and error, respectively. In this study, n_1 and n_2 were set as 2. *F* distribution table shows that $F_{0.01}(2,2)=99.01$, $F_{0.05}(2,2)=19.0$ and $F_{0.1}(2,2)=9.0$. The *F* value of factor A is recorded as F_A. Generally speaking, if $F_A>F_{0.01}(2,2)$, then changes in factor level may have important influences on test results. These changes are denoted as "+ + +." If $F_{0.01}(2,2)>F_A>F_{0.05}(2,2)$, then changes in factor level have considerable influences on test results and are denoted as "+ +." If $F_{0.05}(2,2)>F_A>F_{0.1}(2,2)$, then the changes in factor level have certain influences on test results and are denoted as "+." If $F_A<F_{0.1}(2,2)$, then changes in factor level lack significant influences on test results.

According to the variance analysis presented in Table X, The correlation coefficient R^2 of the freeze-thaw splitting strength ratio is lower than 0.95, indicating the poor fitting effect of the model. The calculated *F* value has no value for comparison. The use of dynamic stability and failure strain as control indexes in the mixing ratio design of mixture is more reasonable. The rejuvenator and RAP can influence the high-temperature stability of recycled mixes significantly, followed by new asphalt. The rejuvenator

Variance source		Square sum of deviation	DOF	F value	Significance	R^2
Dynamic stability	Rejuvenator	210388.667	2	65.610	+ +	0.990
	RAP	71600.667	2	22.378	+ +	
	New asphalt	37845.000	2	11.802	+	
	Error	32066.667	2			
Failure strain	Rejuvenator	253404.667	2	15.626	+	0.955
	RAP	4234.000	2	2.604	Not significant	
	New asphalt	46354.667	2	2.858	Not significant	
	Error	16216.667	2			
Freeze-thaw splitting strength ratio	Rejuvenator	240.042	2	4.764	Not significant	0.948
	RAP	581.109	2	11.532	+	
	New asphalt	89.056	2	1.767	Not significant	
	Error	50.389	2			

Table X . Variance analysis

can influence low-temperature resistance to mixture cracking to some extent. New asphalt has no significant improvement in low temperature crack resistance and water stability.

4.2.3 Intuitive analysis of pavement performance

On the basis of the above analysis, the rejuvenator and RAP can improve the aging performance of HIR mixtures more than new asphalt. For a highly intuitive observation of the action mode, the optimal combination of the mixture was chosen from range analysis. Combining with the fitting effect of evaluation indexes and the significance of influencing factors in range analysis, the histograms of dynamic stability and failure strain with dosages of new asphalt (0), rejuvenator (4% and 5%) and RAP (60%, 70%, 80%, 90%, and 100%) are illustrated in Fig. 6.

As shown in Fig. 6, the dynamic stability of the recycled mixture declines and the failure strain increases with the increase in rejuvenator dosage. With the increase in RAP dosage, the dynamic stability of recycled mixture increases continuously, whereas the failure strain declines. Under all selected conditions, the dynamic stability of the mixture is far higher than that of the standards. When the dosage of the rejuvenator and RAP are 4% and 100%, the dynamic stability reaches the peak, which is 2.6 times that of the standards. When the dosage of the rejuvenator and RAP are 5% and 60%, respectively, the failure strain of recycled mixture peaks. When the dosage of the rejuvenator and RAP are 4% and 80%, respectively, the failure strain of the mixture approaches the critical value gradually. Therefore, although RAP can promote the high-temperature stability of the recycled mixture, it will exert negative effects on low-temperature resistance to cracking. Although the high-temperature performance of the recycled mixture decreases with the increase in rejuvenator dosage, its low-temperature performance increases accordingly. To ensure the high-temperature and low-temperature stability of recycled materials, the dosage of rejuvenator and RAP should be considered comprehensively.

The mix design by orthogonal test can directly show the influence degree of different ingredients on road performance, balance the contradiction among different control levels, and improve efficiency significantly. The aforementioned analyses suggest that the dose of rejuvenator should be controlled at 5%, which has more promotion on physical and chemical performance of aged asphalt, and the ratio of RAP and new asphalt should be 80% and 0%, respectively

5. ECONOMIC BENEFITS AND ENVIRONMENTAL BENEFITS

The material costs and carbon emission related to the different recycling methods were calculated in Table XI.

The proposed design method for hot in-place recycled mixtures has prominent economic and environmental benefits. Economically, the increasing cost of raw material imposes a heavy burden on the pavement maintenance department. This design method increases the utilization of RAP. In comparison with traditional recycling and virgin mixture, the cost of raw materials per ton decreases by 36.2 and 68.5 dollars, respectively. Moreover, the HIR technology can recycle wastes in site, thereby saving additional expenditures for material transportation. Thus, the whole pavement repair project saves costs.

From the environmental perspective, greenhouse gases emission is an important problem that threatens human survival. Asphalt production and material transportation generate significant carbon emissions during pavement repair. Several studies have emphasized that asphalt waste per ton generates approximately 0.02 tons of CO_2 equivalence [29], whereas mixtures per ton generates 0.3 kg of CO_2 at the average transport distance of 20 km [30]. Table XI shows that these pollution problems could be decreased by HIR technology effectively. The total CO_2 emission of the proposed method is 5% of the virgin mixture, and 8% of the traditional recycled mixture.

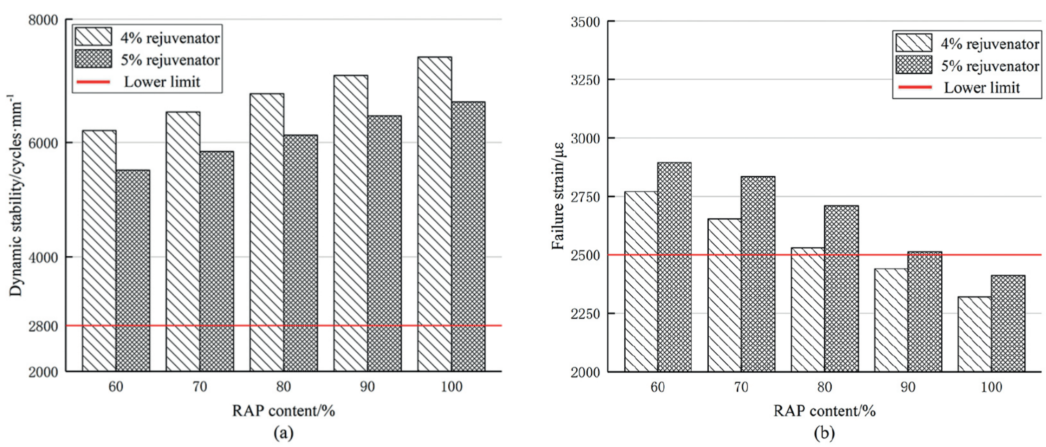

Fig. 6. Test results. (a) The rutting test. (b) The trabecular bending rheological test

Method	RAP content	Cost of asphalt mixture (USD/t)						CO_2 emission (kg/t)		
		Transportation (20km)	Aggregate	RAP	Rejuvenator	New asphalt	Total cost	Asphalt production	Transportation (20km)	Total emission
Virgin mixture	0%	3	112.8	0	0	25.4	141.2	0.7	0.24	0.94
Traditional recycled mixture	30%	2.1	78.9	12.6	8.2	7.1	108.9	0.42	0.17	0.59
Hot in-place recycled mixture	80%	0.6	22.5	33.8	15.8	0	72.7	0	0.05	0.05

Table XI . Analysis of economic and environmental benefits

6. CONCLUSION

The dynamic shearing rheological test is introduced on the basis of the physicochemical property test to set up a mixing ratio design method for hot in-place recycled mixtures. The recycling mechanism of the rejuvenator in aged asphalt mixture is analyzed. Moreover, the influences of the rejuvenator, RAP, and new asphalt on the pavement performance of hot in-place recycled mixtures. are investigated. Some major conclusions could be drawn as follows:

(1) The rejuvenator can improve the physical performance and chemical compositions of the aged asphalt mixture. The viscosity of the recycled asphalt shows linear relations with needle penetration, softening point, and ductility.

(2) The rejuvenator can improve the low-temperature fatigue cracking performance of aged asphalt. Such improvement effect is highly prominent under low temperature. A threshold for rejuvenator dosage exists. The recycling effect declines considerably when the rejuvenator dosage exceeds 30%.

(3) Rejuvenator and RAP dosages are the primary factors that influence the pavement performance of the hot in-place recycled mixture. Although RAP can promote the high-temperature stability of the recycled mixture, it causes negative effects on low-temperature resistance to mixture cracking. The high-temperature performance of recycled mixture deteriorates with the increase in rejuvenator dosage, whereas low-temperature performance is improved.

(4) When the dosage of the rejuvenator, RAP, and new asphalt are 5%, 80%, and 0%, respectively, the recycled mixture can meet standards of high-temperature stability, low-temperature resistance to cracking, and water stability. The proposed method is well applied in practical engineering and achieves extensive economic and environmental benefits. Therefore, the proposed method is feasible in HIR projects.

The proposed mix design method for hot in-place recycled materials has clear ideas, reasonable process, limited parameters, and strong targeting performance. It can provide references for hot in-place recycled projects of asphalt pavement. Nevertheless, given the limitations of article length, this study only selected several important influencing factors despite the complex composition of hot in-place recycled mixtures, resulting in the insufficient sample size. Future studies should involve other influencing parameters to provide great assistance to the development of HIR technology.

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