

Study on the factors affecting temperature and workability during the mixing process of hot in-place recycled asphalt mixtures (RHMA)

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ABSTRACT

The temperature characteristics and workability of Recycled Hot Mix Asphalt (RHMA) are critical determinants of pavement construction quality. This study investigates these factors by conducting an orthogonal mixing experiment, considering four variables-aggregate gradation, asphalt content, mixing time, and preheating temperature of reclaimed asphalt pavement (RAP) – each at four levels, with RAP contents of 30%, 40%, and 50%. An infrared thermal imager is employed to measure the temperature, and the workability evaluation index is calculated based on the motor's output power. The analysis revealed that higher RAP content adversely impacts both heating efficiency and workability. RAP preheating temperature emerged as a dominant factor, significantly affecting temperature uniformity and the final mixing temperature. Insufficient RAP preheating can be mitigated by overheating new aggregate to compensate for the temperature deficit. The relative influence of factors on low-temperature regions follows the order: RAP preheating temperature > mixing time > asphalt content > gradation index. With increasing RAP content, the influence of RAP preheating temperature on RHMA workability becomes more pronounced, while the remaining factors influence workability in the order: mixing time > gradation index > asphalt content. This study offers valuable insights into the temperature and workability dynamics of RHMA during the hot-mix process, providing a theoretical basis for optimizing mixing parameters and improving construction quality.

Keywords: Recycled hot mix asphalt; Orthogonal experiment; Mixing temperature; Mixing workability.

1. INTRODUCTION

Each year, the maintenance of asphalt pavements generates a significant amount of reclaimed asphalt pavement (RAP), and the effective management of this material remains a significant challenge [1, 2]. Hot recycled asphalt mixture (RHMA) is produced by combining waste asphalt with new materials in specified proportions and heating the mixture. This process enables the recycled mixture to achieve performance comparable to that of new asphalt mixtures, offering substantial environmental and economic benefits [3]. In RHMA production, the mixing temperature is a critical process parameter that directly affects the mixture's performance. NAVARO *et al.* [4] found that lower mixing temperatures require longer mixing times, and higher temperatures improve temperature uniformity within the mixture for the same mixing duration. ZHAO *et al.* [5] discovered that higher RAP preheating temperatures result in denser gradation and better performance, and identified a critical RAP preheating temperature of 130°C. ZHAO *et al.* and DING *et al.* [6, 7] concluded that the mixing effect of aged asphalt improves with increases in temperature and time, determining that the optimal wet mixing time is 30 seconds. Therefore, the main factors affecting the temperature in the mixing process are RAP content, RAP preheating temperature, gradation, and mixing time.

Currently, there is limited research on temperature uniformity in RHMA, with most studies focusing on temperature segregation during the paving and compaction stages. During the mixing phase of RAP-containing recycled asphalt mixtures, dispersion and agglomeration behaviors occur [8], and uneven mixing temperatures are equally detrimental to performance as gradation segregation [9]. Low mixing temperatures are a primary cause of poor paving quality in asphalt pavements. Traditionally, the main method for monitoring temperature

segregation in recycled asphalt mixtures has been the use of temperature guns, which have clear limitations such as limited measurement range, data delays, high variability, and are time-consuming, labor-intensive, and subject to randomness. With advances in infrared thermal imaging technology, surface temperature data can now be directly captured, offering broader measurement range, increased data availability, and improved accuracy [10]. PLATI *et al.* [11] demonstrated that infrared thermal imaging systems are a fast, effective, and practical nondestructive tool for testing the temperature of hot mix asphalt (HMA) on site. HAN [12] further confirmed this by using an infrared thermal imaging (ITI) system to monitor the heating process during in-place hot recycling (HIR). Therefore, utilizing infrared imaging technology to monitor temperature changes during the RHMA mixing process is an effective method.

The better the workability of the asphalt mixture, the easier it is to mix, pave, and compact into high-quality asphalt pavement, which is crucial for ensuring construction quality [13, 14]. However, in practical engineering applications, workability lacks specific quantitative indicators for assessment [15]. In current practice, viscosity testing of asphalt binders is commonly used as a key indicator to assess the mixture's workability. However, this viscosity-based method neglects the cohesion between the aggregate and the asphalt binder [16]. Additionally, some researchers have used the void ratio of Marshall specimens under constant compaction effort and parameters such as locking points and compaction curves generated by gyratory compactors as workability indicators [17]. Since the gyratory compaction method is highly insensitive to temperature [18], researchers have realized that it is not well suited for studying recycled asphalt mixtures [19]. Currently, workability evaluation methods typically rely on either the mixing torque method or the mixing current method [20]. However, variability in torque test values is influenced by equipment stiffness, the particle size of the mixture, and the precision of the torque sensor, making quantitative analysis of asphalt mixture workability challenging [21]. Moreover, since circuit voltage during mixing is affected by fluctuating external input, evaluating asphalt mixture workability solely based on a single current value for mixing power is methodologically flawed [22].

During the mixing process of asphalt mixtures, the motor must overcome the viscous resistance of the mixture to drive the blades or paddles for mixing, meaning the motor's power consumption is inversely proportional to the mixture's workability. By measuring the power curve throughout the mixing process, changes in the mixture's workability at different stages can be monitored in real-time. Power fluctuations at the start and end of mixing can directly reflect the mixture's workability status. This method is simple, fast, and allows for real-time acquisition of quantitative indicators during mixing, making it highly practical. Chen *et al.* [23] proposed a workability evaluation index for asphalt mixtures based on torque values and energy consumption during the mixing process. Yan *et al.* [24] developed a modified asphalt mixture mixer that uses motor power testing to assess mixture workability, studying the effects of asphalt and asphalt mortar on mixture workability. These studies have shown that the workability of asphalt mixtures can be quantitatively characterized using motorized mixer power; however, few studies have considered the effect of influencing factors on the workability during the mixing process, which is extremely detrimental to improving mixing efficiency.

To study the factors influencing the mixing temperature and workability of mixing process of RHMA, this paper conducted a 4-factor, 4-level orthogonal experiment featuring RAP contents of 30%, 40%, and 50%. The factors included aggregate gradation, asphalt content, mixing time, and RAP preheating temperature. Infrared thermal imaging was used to capture temperature data at various stages of the mixing process, and these data were extracted from specific regions to explore the effects of different factors on heat transfer and temperature uniformity during RHMA mixing. Additionally, with RAP contents of 0%, 30%, 40%, and 50%, power data from the 4-factor, 4-level orthogonal experiment were recorded to calculate the workability index of RHMA, and the effects of various factors on workability were analyzed. The objective of this study is to investigate the main factors influencing mixing temperature and workability, providing scientific evidence to optimize RHMA production processes.

2. MATERIALS AND METHODS

2.1. Materials

The RAP used in this study was sourced from the milling of a municipal asphalt pavement in Nanchang, China. After crushing and screening, it was divided into three sizes: 0–6 mm, 6–10 mm, and 10–16 mm (Figure 1(a)). Both the aged asphalt and old aggregate were recovered from these RAP materials, with their basic properties shown in Table 1. The new asphalt used was SBS-modified asphalt, with its performance data detailed in Table 2. The asphalt content was set at four levels: 3.7%, 4.0%, 4.3%, and 4.6%. The new aggregate used in the experiment was limestone, which was washed and dried before being screened into 11 sizes according to standard sieve diameters for asphalt pavement aggregates, ensuring the accuracy of RHMA gradation (Figure 1(b)). The performance of the aggregate met all the requirements of JTG 3432-2024.

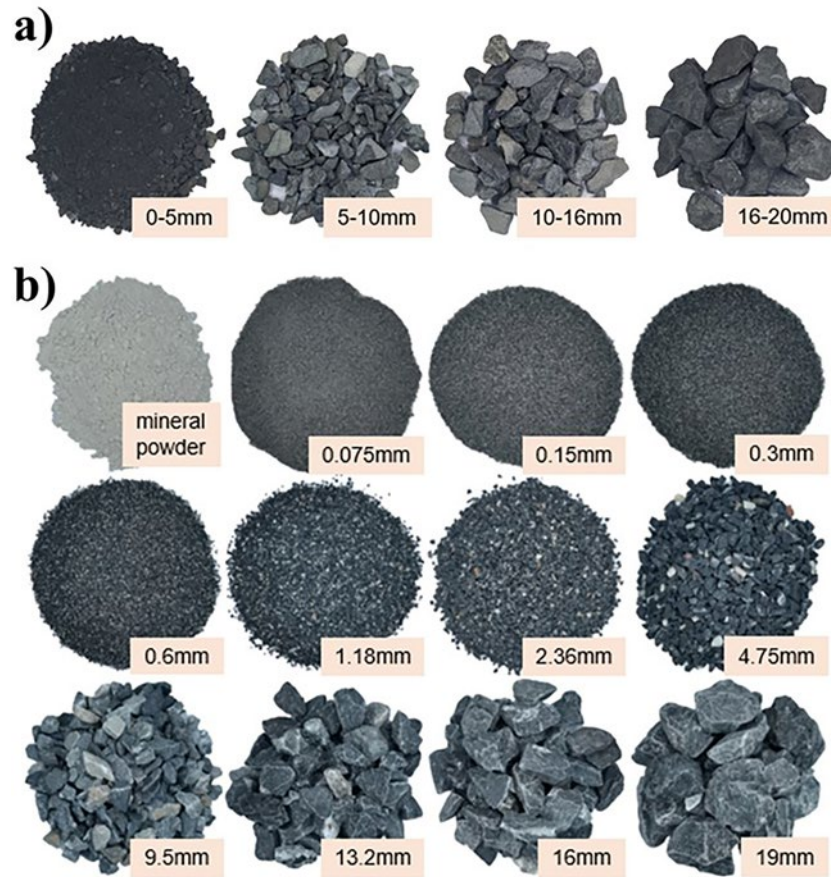


Figure 1: Sieved aggregate (a) recycled aggregate; (b) new aggregate.

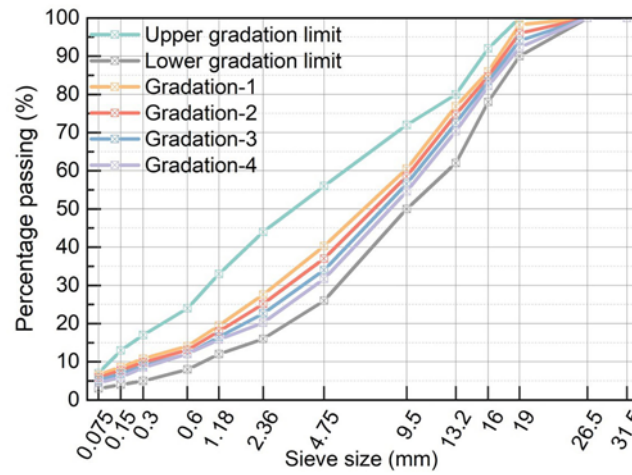
Table 1: RAP technical indicators.

MATERIAL	TESTING ITEMS		TEST VALUE	TECHNICAL REQUIREMENTS
Aging asphalt	(25°C, 100 g, 5 s) Penetration (0.1 mm)		32.7	≥ 10
	Softening point (°C)		56.2	—
	(5 cm · min ⁻¹ , 15°C) Ductility (cm)		13.1	—
	135°C dynamic viscosity (Pa · s)		963.52	—
	Density (g/cm ³)		1.031	—
Recycled aggregate	Flaky and elongated particle content (%)		9.6	≤ 15
	Crushing value (%)		22.3	≤ 28
	Apparent relative density (g/cm ³)	0–6 mm	2.722	≥ 2.5
		6–10 mm	2.723	
		10–16 mm	2.730	
	Bulk specific gravity (g/cm ³)	0–6 mm	2.706	
		6–10 mm	2.674	
		10–16 mm	2.660	

The gradation used in this study was a coarse dense-graded AC-20C. To illustrate the variability in gradation, four gradations with different coarseness levels were selected, as shown in Figure 2. To better characterize the aggregate gradation, a “gradation index” was used, that represents the difference between the passing

Table 2: SBS-modified asphalt technical indicators.

TESTING ITEMS		TEST VALUE	TECHNICAL REQUIREMENTS
(25°C, 100 g, 5 s) Penetration (0.1 mm)		44.7	30–60
Softening point (°C)		71.8	≥60
(5 cm · min ⁻¹ , 5°C) Ductility (cm)		36.7	≥20
135°C dynamic viscosity (Pa · s)		2.13	≤3
Flash Point (°C)		352	≥230
Solubility (%)		99.89	≥99
Density (g/cm ³)		1.029	–
TFOT (or RTFOT) Residue after	Mass change (%)	0.53	≤1
	25°C Penetration ratio (%)	82.8	≥65
	(5 cm · min ⁻¹ , 5°C) Ductility (cm)	28.6	≥15

**Figure 2:** Gradation curve of RHMA.

percentages of the gradation and the corresponding maximum density curve at each sieve size. The formulas for calculating the gradation index are provided in equations (1) and (2), where: P_i is the passage rate of a screen i of a mineral grade; P_{LL} is the passage rate of a screen i on the theoretical maximum density curve; d_i is a screen size; D is the minimum screen size that ensures that the largest size aggregate can pass, and GI is gradation index. The gradation indices for the gradation curves used in this study, Gradation 1–4, were calculated to be 50.2, 57.2, 65.3, and 76.8, respectively.

$$P_{LL} = \left(\frac{d_i}{D} \right)^{0.45} \times 100 \quad (1)$$

$$GI = \sum |p_i - p_{LL}| \quad (2)$$

2.2. Workability test

Real-time power data were continuously collected throughout the RHMA mixing process. For quantitative evaluation of workability, the reciprocal of the motor's effective power consumption during mixing is used as the

workability index. The formula for calculating this index is provided in Equation (3), where I represent the workability index, S is the area under the power curve, T is the total mixing time, W is the real-time power measured during the test, and W_s is the lower limit of stirring power.

$$I = \frac{1}{S \times \frac{60}{T}} = \frac{1}{\sum_{i=1}^T (W - W_s) \times \frac{60}{T}} \quad (3)$$

This method provides insight into how power consumption changes throughout the mixing process, and the workability index offers a quantifiable measure for analyzing the mixture's workability.

2.3. Preheating temperature setting

To maintain consistent final mixing temperatures for RHMA (between 150–160°C), the preheating temperatures of different materials vary depending on the specific test combinations. Based on prior research and construction experience, the RAP preheating temperatures and new aggregate heating temperatures used in this study are shown in Table 3.

2.4. Mixing test

The mixing test apparatus consists of three primary components: a mixing system, a power monitoring system, and a data storage system, as depicted in Figure 3. The mixing system includes an automatic asphalt mixture mixer, model SYD-F02-20, manufactured by Shanghai Changji Geological Instrument Co., Ltd. This mixer is designed in accordance with T0702-2011 standards specified in JTG E20-2011, with flexible settings for both mixing time and temperature. The power monitoring system relies on a three-phase electric power tester (model YP9830, 20A) from Yongpeng Instrument Co., Ltd., which monitors the mixer's real-time power consumption, collecting data every second. This power tester is equipped with communication functions and features USB and RS-232 interfaces for data transfer.

The mixing test procedure follows a structured sequence: material preparation, drying, batching, preheating, software initialization for data collection, mixing/data collection, and data saving. The mixer is started 30 minutes prior to the test, and its heating system is activated to ensure the mixing bowl is fully preheated. During the preheating stage, all materials are placed in an oven at the required temperature for 3 hours. Once this period ends, a temperature gun is used to verify the temperature of each material. The mixing process starts as soon as the materials reach the desired temperature. At 150 minutes into the preheating, the mixing bowl is turned on and heated to 160°C. The mixing sequence begins with the preheated RAP being added to the mixing bowl, and the first infrared thermal image is taken, marking this time as T0. After the rejuvenator is added, dry mixing starts, and the second infrared image is captured, with the time marked as T1. Afterward, new aggregate and new asphalt are added, and wet mixing begins. The third infrared image is taken upon completion of the wet mixing stage, with the time recorded as T2. Finally, after adding mineral powder and completing the final mixing, the fourth infrared image is taken, with the time marked as T3. All images are taken within 5 seconds

Table 3: Preheating temperature.

CONTENT OF RAP (%)	PREHEATING TEMPERATURE OF RAP (°C)	PREHEATING TEMPERATURE OF NEW AGGREGATE (°C)	PREHEATING TEMPERATURE OF NEW ASPHALT (°C)
30	90	190	160
	110	180	160
	130	170	160
40	90	200	160
	110	190	160
	130	180	160
50	90	210	160
	110	200	160
	130	190	160

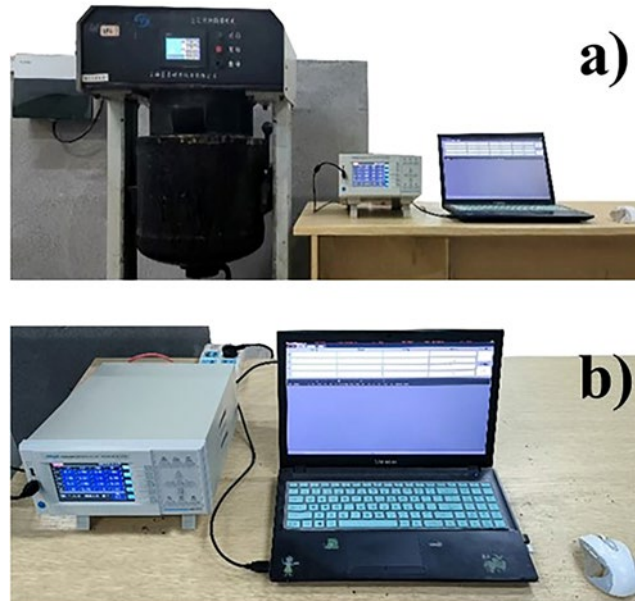


Figure 3: Mixer power testing device (a) mixing device; (b) display device.

after the mixing bowl stabilizes. The stages of the mixing process are categorized as follows: T0 marks the start of mixing, T0-T1 represents the dry mixing phase, T1-T2 the wet mixing phase, T2-T3 the final mixing phase, and T3 the end of mixing.

3. RHMA MIXING TEMPERATURE

3.1. Temperature distribution during RHMA mixing

The temperature variations during the RHMA mixing process are divided into two main phases. In the first phase, the RAP absorbs heat, causing its temperature to rise, while the new aggregate loses heat, lowering its temperature. As a result, the entire mixture maintains a uniform elevated temperature. In the second phase, after the RAP is dispersed and disintegrated, the old and new aggregates, as well as the aged and fresh asphalt, are fully mixed under mechanical stirring, resulting in a homogeneous mixture. To examine the temperature changes throughout the mixing process, this section analyzes the temperature distribution data during the mixing of RHMA containing 30% RAP. The temperature distribution changes during the mixing process are shown in Figure 4. According to construction technical specifications, the compaction temperature of SBS-modified asphalt mixtures must exceed 150°C, while mixing asphalt mixtures at temperatures above 170°C can accelerate the aging of recycled asphalt. Therefore, areas where the RHMA temperature is below 150°C are defined as low-temperature zones, while areas above 170°C are considered high-temperature zones.

As shown in Figure 4, the temperature distribution at T0 is concentrated, as the RAP was uniformly preheated in the oven before T0. At T1, the temperature distribution range increases, the temperature distribution curve becomes shorter, and shifts toward higher temperatures. This occurs because the RAP efficiently absorbs heat from the mixing bowl during the dry mixing stage, raising its temperature. However, due to the short mixing time, the heating of the RAP remains uneven, leading to a significant temperature gradient within the RAP. When the RAP preheating temperature is 90°C, the temperature at T1 remains in the low-temperature zone, while when the RAP preheating temperature is 130°C, the probability of exceeding 150°C at T1 is 33.6%, indicating that RAP preheating temperature significantly influences the dry mixing temperature. At T2, the temperature distribution range further increases, the temperature curve rises slightly, and shifts quickly toward higher temperatures. This occurs because, as the high-temperature new aggregate mixes with the RAP, the RHMA's overall temperature rises. However, due to limited mixing time, some RAP within the RHMA does not heat sufficiently, resulting in distinct low- and high-temperature zones. The lower the RAP preheating temperature, the more pronounced are the changes in the temperature curve, with a larger proportion of low-temperature zones and increased temperature distribution unevenness. This occurs because lower RAP preheating temperatures

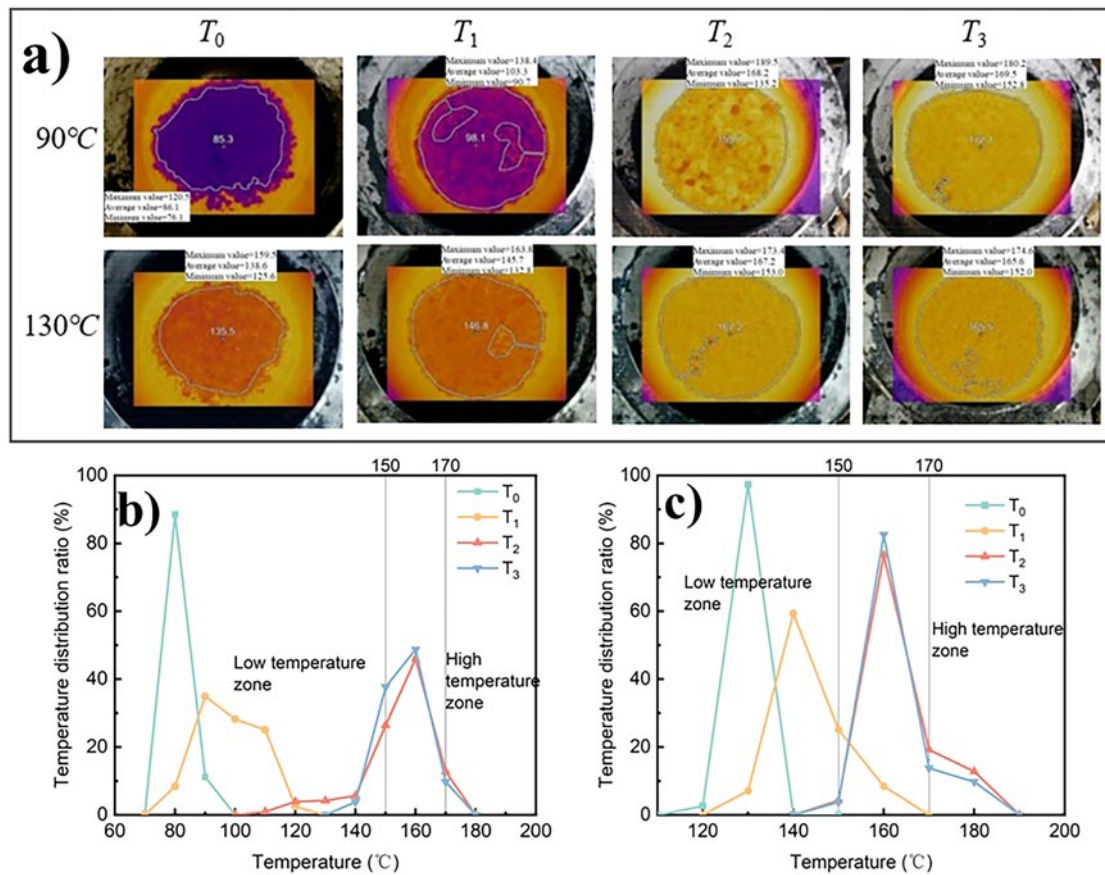


Figure 4: Temperature changes during mixing process: (a) RAP preheating temperature 90, 130°C mixing the whole process of infrared thermograms; (b) RAP preheating temperature 90°C; (c) RAP preheating temperature 130°C.

require more time for the RAP to heat and disintegrate. When the mixing time is insufficient, the RHMA's temperature distribution becomes more uneven. At T_3 , compared to T_2 , the temperature distribution range narrows, and the low- and high-temperature zones diminish, with temperatures concentrating in the middle range. This indicates that during continued mixing, the high-temperature new aggregate continues to exchange heat with the low-temperature RAP, leading to a more uniform RHMA temperature.

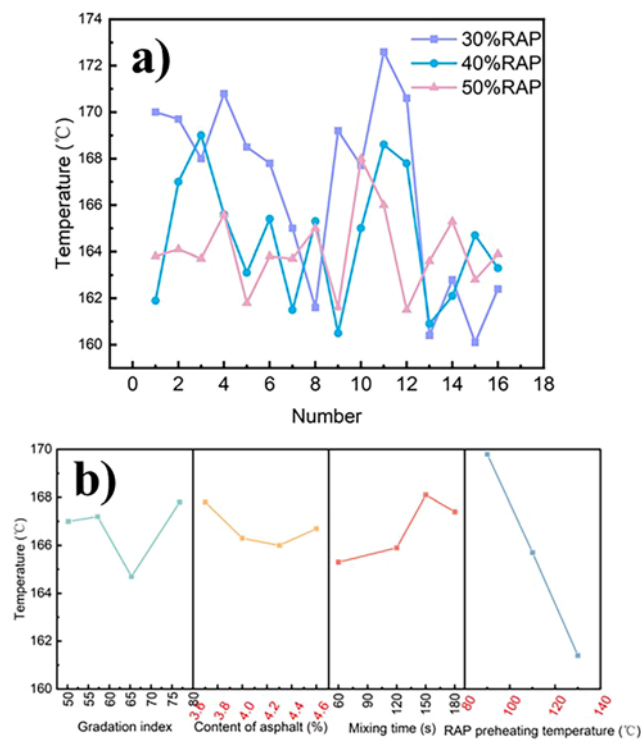
In summary, the temperature changes during the three mixing stages are as follows: During the T_0 - T_1 dry mixing stage, the RAP's temperature increases slightly through contact with the mixing bowl, and mechanical action contributes to partial disintegration and separation of RAP, initiating the mixing process. The T_1 - T_2 wet mixing stage is the primary phase for temperature increase, during which the overheated new aggregate fully combines with the low-temperature RAP, exchanging heat and significantly raising the overall RHMA temperature. Simultaneously, mechanical stirring and friction between components further disperse and disintegrate the RAP, ensuring thorough mixing. In the T_2 - T_3 final mixing stage, continued heat exchange between the high-temperature new aggregate and low-temperature RAP reduces temperature variations, resulting in a more uniform RHMA temperature. The RAP preheating temperature significantly influences the temperature uniformity of the mixture.

3.2. Factors affecting end-of-mix temperature

To study the effects of temperature at the end of mixing, a statistical analysis was conducted on the T_3 (end of mixing) temperature for 48 groups of RHMA with varying RAP content, gradation, asphalt content, mixing times, and RAP preheating temperatures. The results are presented in Table 4 and Figure 5(a). As shown in Table 4, over 90% of T_3 values fall within the optimal paving temperature range of 160-170°C, indicating that the orthogonal experiments in this study meet the design specifications. Figure 5(a) illustrates that the higher the RAP content, the smaller the fluctuations in T_3 , suggesting that high RAP content reduces temperature sensitivity. To further investigate the effects of the other four factors on RHMA temperature sensitivity,

Table 4: The temperature of RHMA at the end of mixing.

NUMBER	GRADATION INDEX	CONTENT OF ASPHALT (%)	MIXING TIME (s)	RAP PREHEATING TEMPERATURE (°C)	TEMPERATURE (°C)		
					30% RAP	40% RAP	50% RAP
1	76.8	3.7	60	90	170.0	161.9	163.8
2	65.3	4.6	150	90	169.7	167.0	164.1
3	50.2	4.3	120	90	168.0	169.0	163.7
4	57.2	4	180	90	170.8	165.6	165.6
5	50.2	3.7	180	110	168.5	163.1	161.8
6	76.8	4.3	150	110	167.8	165.4	163.8
7	57.2	4.6	120	110	165.0	161.5	163.7
8	65.3	4	60	110	161.6	165.3	165.0
9	50.2	4.6	60	90	169.2	160.5	161.6
10	65.3	4.3	180	90	167.7	165.0	168.0
11	57.2	3.7	150	90	172.6	168.6	166.0
12	76.8	4	120	90	170.6	167.8	161.5
13	57.2	4.3	60	130	160.4	160.9	163.6
14	76.8	4.6	180	130	162.8	162.1	165.3
15	65.3	3.7	120	130	160.1	164.7	162.8
16	50.2	4	150	130	162.4	163.3	163.9

**Figure 5:** The relationship between influencing factors and temperature: (a) RAP; (b) gradation index, content of asphalt, mixing time, RAP preheating temperature.

the mean T3 temperature was analyzed under conditions of 30% RAP content using the control variable method, as depicted in Figure 5(b). The analysis reveals that RAP preheating temperature significantly affects the mean T3 temperature of RHMA, showing an inverse relationship: ensuring the same output temperature requires higher preheating of the new aggregate when the RAP preheating temperature is lower. This causes a portion of the new aggregate to retain higher heat, leading to an elevated overall temperature. In contrast, asphalt content, mixing time, and gradation index show minimal impact on temperature variations at the end of RHMA mixing.

3.3. Factors affecting end-of-mix low temperature zone

When the mixture temperature is low at the end of mixing, it directly impacts construction operations, particularly by increasing the difficulty of paving and compaction, which, in turn, affects the density, strength, and durability of the pavement structure. Therefore, the proportion of RHMA in the low-temperature zone at T3 was calculated under different influencing factors, as shown in Figure 6. From Figure 6, it is observed that increasing RAP content raises the proportion of RHMA in the low-temperature zone at T3, indicating that excessive RAP content negatively affects the heating efficiency of RHMA. No significant correlation is found between gradation index and asphalt content with the proportion of RHMA in the low-temperature zone at T3, while this proportion decreases with increasing RAP preheating temperature and mixing time. To further analyze the impact of the four factors on the low-temperature zone at T3, range and variance analyses were performed, with results presented in Tables 5 and 6.

Table 5 shows that the range of influence on the low-temperature zone proportions is, from largest to smallest: RAP preheating temperature > mixing time > asphalt content > gradation index. According to Table 6, RAP preheating temperature has a statistically significant effect ($P\text{-value} < 0.05$) on the proportion of the low-temperature zone in RHMA after mixing. At 50% RAP content, the $P\text{-value}$ for mixing time is also less than 0.05, showing that mixing time has a moderate influence on the low-temperature zone, with this effect increasing as RAP content rises. The $P\text{-values}$ for gradation index and asphalt content are both above 0.05, indicating that these factors do not significantly affect the proportion of the low-temperature zone. This further demonstrates that the primary factors influencing the end-of-mixing temperature are RAP preheating temperature and mixing time. The primary cause of the low-temperature zone is insufficient RAP heating. The higher the RAP preheating temperature, the less heat is required during mixing, making it easier to exceed the low-temperature zone. Additionally, the heat exchange between RAP and new aggregate takes time, so the longer the mixing time, the more heat RAP absorbs, facilitating the reduction of the low-temperature zone. The degree of influence on the low-temperature zone proportions ranks as follows: RAP preheating temperature, mixing time, asphalt content, and gradation index.

Overall, the preheating temperature of RAP significantly affects temperature uniformity by directly influencing the temperature distribution of recycled aggregate and its compatibility with the blending of new and old asphalt. Mixing time impacts the dynamic distribution of heat, asphalt content adjusts the flowability of the mixture, and the gradation index affects the contact and void ratio between aggregates, all of which collectively influence the uniformity of temperature distribution. Enhancing temperature uniformity during the mixing process is a multifactorial regulatory process that requires simultaneous optimization of both material properties (aggregate gradation and asphalt content) and process conditions (mixing time and RAP preheating temperature). This ensures uniform heat distribution, high-quality mixing of recycled asphalt mixtures, and performance improvement.

4. RHMA WORKABILITY

4.1. Mixing power

To investigate the effect of RAP content on the mixing power of RHMA, the full-process mixing power of HMA and RHMA with varying RAP contents was analyzed. The three test conditions were: Condition I (gradation index: 50.2, asphalt content: 4.3%, mixing time: 120 seconds, RAP preheating temperature: 90°C); Condition II (gradation index: 57.2, asphalt content: 3.7%, mixing time: 150 seconds, RAP preheating temperature: 90°C); and Condition III (gradation index: 76.8, asphalt content: 4.6%, mixing time: 180 seconds, RAP preheating temperature: 130°C).

As shown in Figure 7, the mixing power fluctuates around certain values during different stages, with HMA exhibiting two distinct stages and RHMA showing three. This is because HMA uses a two-stage mixing method, while RHMA employs a three-stage method. At the start of each stage, there is a sharp increase in power, partly due to the need to overcome inertia as raw materials move from a stationary to a dynamic state, and partly because some aggregates are interlocked under gravity before entering the mixing bowl. In the initial stage, the stirring blades must break this pre-arranged structure, requiring higher motor output. In the second

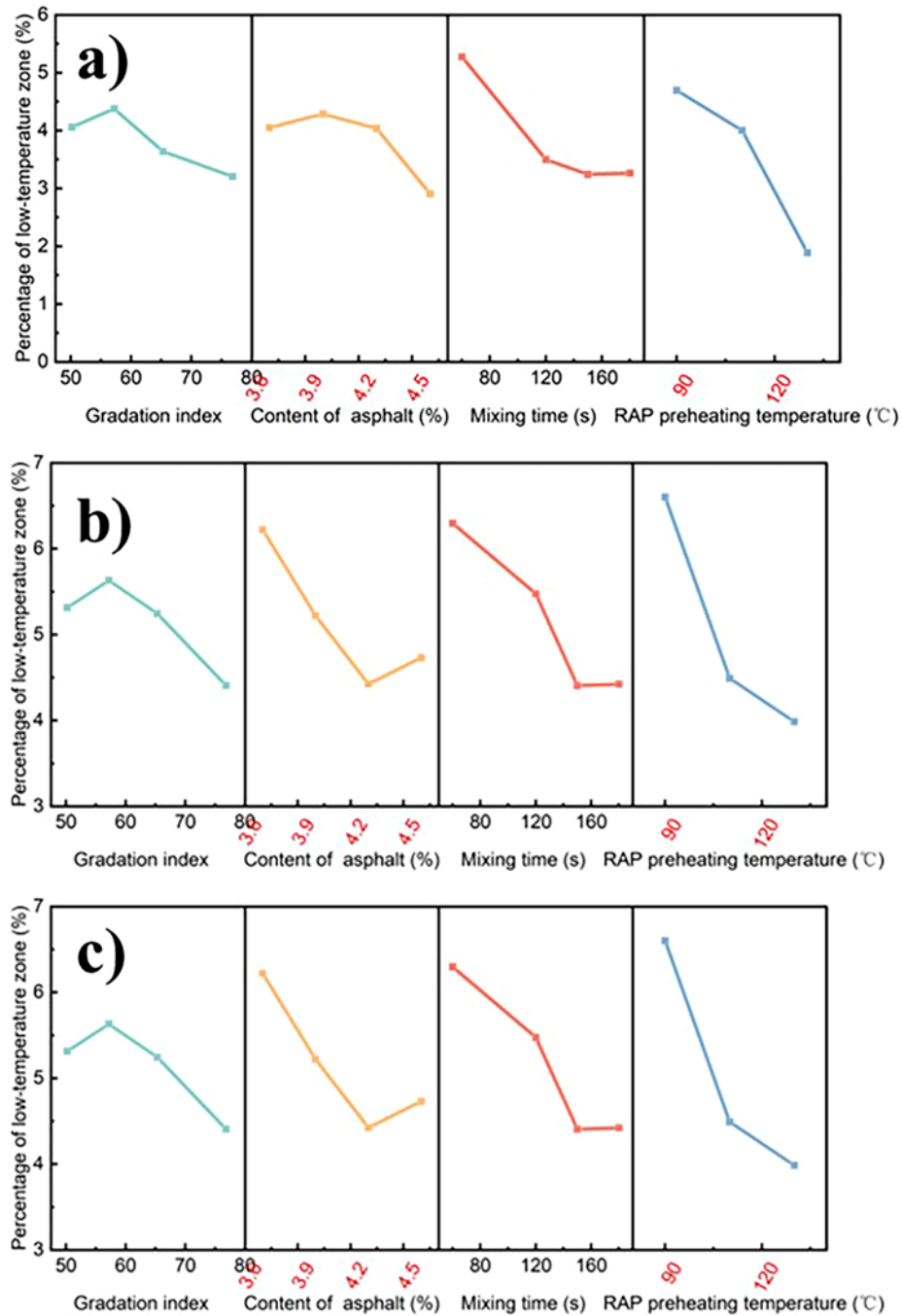


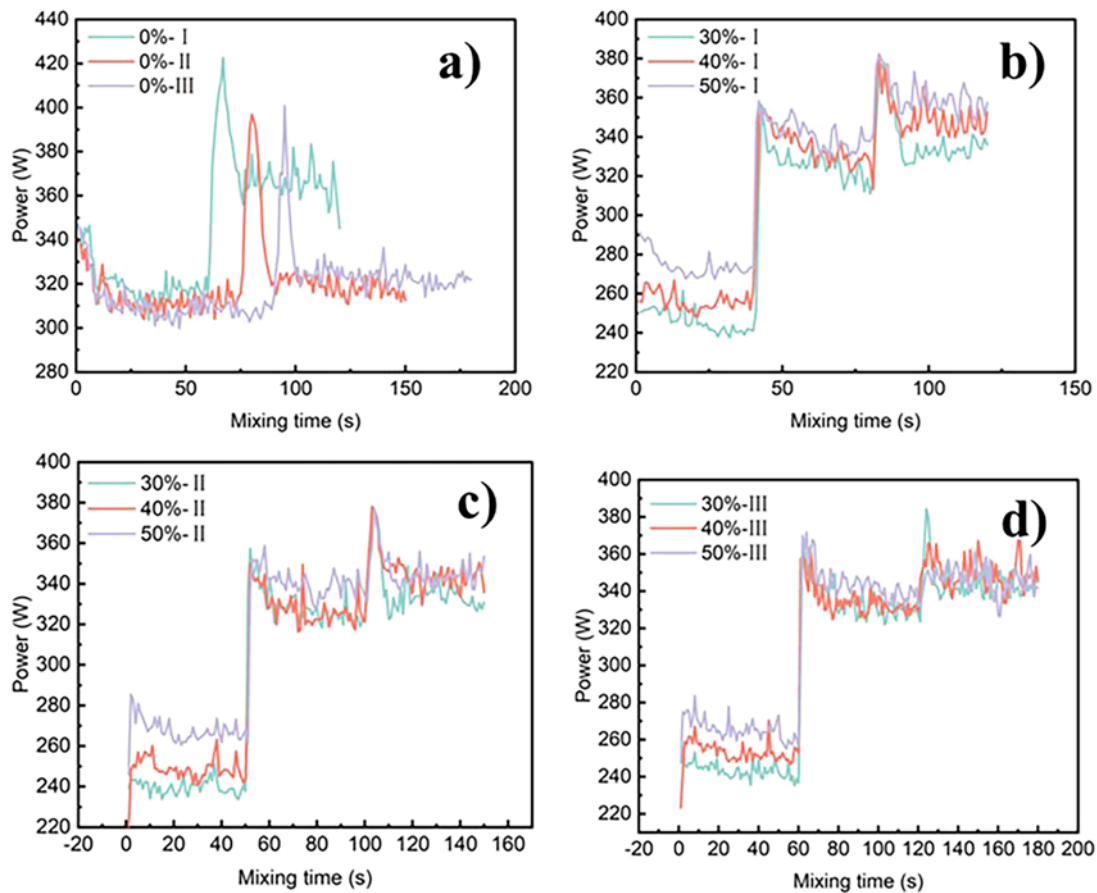
Figure 6: The relationship between influencing factors and the proportion of low-temperature area in RHMA at the end of mixing: (a) 30%RAP; (b) 40%RAP; (c) 50%RAP.

Table 5: Analysis of range for proportions in the low-temperature zone.

CONTENT OF RAP (%)	RANGE			
	GRADATION INDEX	CONTENT OF ASPHALT	MIXING TIME	RAP PREHEATING TEMPERATURE
30	1.173	1.381	2.033	2.807
40	1.224	1.797	1.892	2.007
50	0.387	1.893	2.261	2.932
Average value	0.928	1.690	2.062	2.582

Table 6: Analysis of variance for proportions in the low-temperature zone.

CONTENT OF RAP (%)	VARIANCE			
	GRADATION INDEX	CONTENT OF ASPHALT	MIXING TIME	RAP PREHEATING TEMPERATURE
30	F value	1.04	1.54	3.83
	P value	0.465	0.335	0.114
40	F value	1.19	2.69	3.63
	P value	0.421	0.182	0.123
50	F value	1.71	4.26	7.04
	P value	0.301	0.098	0.045

**Figure 7:** Power variation during mixing of different RHMA: (a) HMA-I, II, III; (b) 30%, 40%, 50%RAP-I; (c) 30%, 40%, 50%RAP-II; (d) 30%, 40%, 50%RAP-III.

stage, RHMA mixing power significantly increases due to the addition of new aggregates, which are heavier and increase mixing resistance. In the second stage of HMA and the third stage of RHMA, mixing power slightly exceeds that of the previous stages. Throughout each stage, mixing power gradually decreases as the asphalt coating lubricates the aggregates, reducing mixing resistance. The addition of materials leads to sharp increases in mixing power, with even small amounts of mineral powder contributing to this rise.

Figure 7(a) demonstrates that the three mixing methods also impact HMA mixing power without RAP, with method I showing a markedly higher power in the second stage compared to the other methods. Figures 7(b), (c), and (d) show that increasing RAP content raises the overall mixing power of RHMA, indicating reduced workability, which aligns with the findings of KUSAM *et al.* [25]. This is due to RAP's tendency to agglomerate, increasing its particle size, and the higher viscosity of aged asphalt in RAP, which leads to greater mixing

resistance. In method I, RHMA mixing power in stages 2 and 3 is lower than that of HMA, while in methods II and III, it is higher than that of HMA, with little difference between the latter two. This suggests that other factors may offset workability issues associated with excessive RAP content, indicating a need for further analysis of how these four factors affect workability.

4.2. Factors affecting workability

To further study the factors affecting workability, mixing power data for RHMA with 30%, 40%, and 50% RAP content were collected, and the workability index was calculated using equation (3). The results are shown in Figure 8. From Figure 8, it is evident that the overall workability index of RHMA decreases with

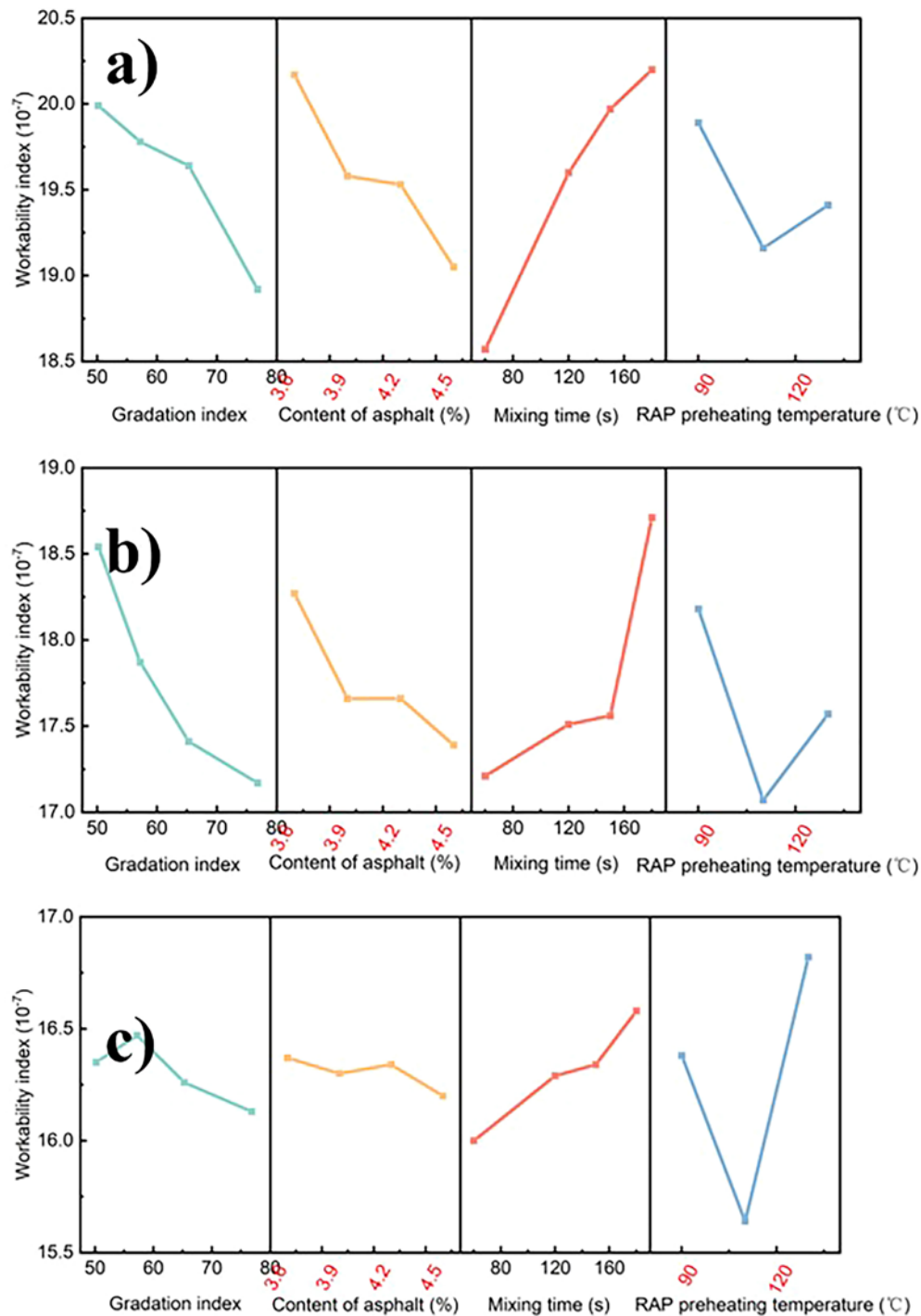


Figure 8: The relationship between influencing factors and RHMA mixing workability: (a) 30%; (b) 40%; (c) 50%.

increasing gradation index, decreases with higher asphalt content, and increases with longer mixing time, showing a clear trend. This suggests that within the range of factors in this experiment, finer gradation, lower asphalt content, and longer mixing time improve RHMA workability, making it better suited for construction. Coarser aggregates require greater stirring force, while longer mixing times create a more uniform mixture, and higher asphalt content increases viscosity, thus reducing workability. To compare the relative influence of these factors on workability, range and variance analyses were conducted on the orthogonal test results, as shown in Tables 7 and 8.

From Table 7, it is apparent that, at any RAP content, the range of mixing time is larger than that of the gradation index and asphalt content. At 30% RAP content, the range of asphalt content exceeds that of the gradation index, while the gradation index shows a larger range at higher RAP contents. Additionally, the range of RAP preheating temperature increases with RAP content, becoming the largest influence from initially being the smallest. This indicates that mixing time has the greatest influence on RHMA workability, followed by RAP preheating temperature, gradation index, and asphalt content. According to Table 8, the P-values of all factors exceed 0.05, indicating that the influence of these factors on the workability index is not statistically significant, likely due to fluctuations in the power data. Except for RAP preheating temperature, the F-values for other RAP contents rank as mixing time > gradation index > asphalt content. The F-value for RAP preheating temperature increases with RAP content. Based on the F-values and range analysis, the most significant factor influencing workability is mixing time, followed by gradation index, asphalt content, and RAP preheating temperature, whose influence increases with rising RAP content. The mixing time has the strongest impact on the workability index because it directly determines the uniformity of material mixing and adhesion effects. The gradation index influences workability by affecting the skeleton structure of the mixture and the thickness of the asphalt film, while asphalt content affects workability through its lubrication effect. The interactive effect of RAP preheating temperature and RAP content involves factors such as the blending of new and aged asphalt, the softening of aged asphalt, and secondary aging, all of which influence workability. Overall, mixing time, gradation index, and asphalt content respectively affect workability from the perspectives of process, material, and proportioning, while the interaction between RAP preheating temperature and RAP content is a variable that requires special attention in RAP mixtures. The mechanisms of these factors are interconnected and collectively determine the workability level of recycled asphalt mixtures.

Table 7: Analysis of range for workability index.

CONTENT OF RAP (%)	RANGE			
	GRADATION INDEX	CONTENT OF ASPHALT	MIXING TIME	RAP PREHEATING TEMPERATURE
30	1.07	1.11	1.63	0.73
40	1.37	0.88	1.50	1.11
50	0.34	0.18	0.58	1.18
Average value	0.93	0.72	1.24	1.01

Table 8: Analysis of variance range for workability index.

CONTENT OF RAP (%)		VARIANCE			
		GRADATION INDEX	CONTENT OF ASPHALT	MIXING TIME	RAP PREHEATING TEMPERATURE
30	F value	1.34	1.30	3.24	1.23
	P value	0.38	0.389	0.143	0.383
40	F value	2.89	1.11	3.48	3.41
	P value	0.166	0.444	0.130	0.137
50	F value	0.33	0.09	0.90	5.76
	P value	0.807	0.959	0.514	0.066

5. CONCLUSIONS

Through infrared thermal imaging analysis and motor output power data collection during the entire RHMA mixing process, this study examined the temperature evolution of various RHMA mixtures during mixing. The impact of several factors on temperature was evaluated using metrics such as temperature distribution, average temperature, and the proportion of low-temperature zones. An evaluation index for RHMA workability was developed to assess the impact of different factors. The key findings of this study are as follows:

- (1) The temperature evolution during RHMA mixing can be divided into three stages: the dry mixing stage (T0 to T1), where RAP undergoes limited heating but largely remains in the low-temperature zone; the wet mixing stage (T1 to T2), the primary stage of temperature rise, during which overheated aggregates mix thoroughly with low-temperature RAP, significantly increasing the overall temperature and yielding a fully mixed RHMA; and the final mixing stage (T2 to T3), where continued heat exchange between aggregates and RAP reduces temperature differentials, improving the uniformity of the mixture. Of these stages, the preheating temperature of RAP significantly influences temperature uniformity and the final mixing temperature.
- (2) Over 90% of the test groups had an average mixing end temperature between 160–170°C. Excessive RAP content reduces RHMA heating efficiency, but increasing RAP preheating temperature mitigates the resulting temperature non-uniformity. The proportion of the low-temperature zone in RHMA decreases with increasing RAP preheating temperature and mixing time. The degree of influence of each factor on the low-temperature zone at different RAP contents follows the order: RAP preheating temperature > mixing time > asphalt content > gradation index.
- (3) After each stage of mixing, the mixing power decreases, but the addition of raw materials causes a sharp increase in power. The greater the mass of the added materials, the larger the increase in mixing power. Higher RAP content reduces RHMA workability, but adjustments to other factors can mitigate these issues. The RHMA workability index generally decreases with increasing gradation index and asphalt content and increases with longer mixing time. The influence of RAP preheating temperature on RHMA workability increases with RAP content, while the influence of the other three factors on the workability index, from strongest to weakest, is mixing time > gradation index > asphalt content.

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