



## Research on the Improvement Effect of Asphalt Mixture Workability Based on Uniform Material Distribution

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### Abstract

Asphalt mixture workability (WAM) is critical for quality control during asphalt pavement construction. However, the methods to improve mixing quality and the impact of such improvements on material distribution uniformity remain unclear. This study aims to identify WAM enhancement strategies and explore their effects on the distribution uniformity of asphalt, aggregates, and asphalt films at the asphalt-aggregate interface. Methods include verifying the potential of mixing temperature elevation and warm mix additives (WMAs) to improve WAM, introducing three evaluation indices (asphalt distribution uniformity index ADU, aggregate distribution uniformity index HA, and asphalt film coating uniformity index AUAF), and analyzing the impacts of workability improvements on post-mixing material uniformity. Findings show that raising mixing temperature (up to 13% WAM enhancement) and adding WMAs (Sasobit boosts WAM by 10%) effectively enhance WAM; WMAs reduce the viscosity of SBS-modified asphalt during high-temperature mixing, weakening asphalt-aggregate bonding and promoting aggregate migration; higher mixing temperatures and WMAs both decrease the asphalt film coating uniformity index, with temperature exerting a more prominent effect. The innovation lies in establishing quantitative evaluation indices and revealing the intrinsic mechanism of WAM improvements on multi-dimensional material distribution uniformity, providing a theoretical basis for asphalt mixture quality optimization.

*Keywords:* Workability; Asphalt Mixture; Improvement; Modifying Agents; Warm Mix Agent.

### 1. Introduction

Asphalt pavement is extensively used in highway construction due to its superior properties, such as high smoothness, no joints, comfortable driving experience, low noise levels, and convenient maintenance [1, 2]. With economic growth, the adoption of asphalt pavement is expected to increase annually, and the rise in traffic volume and vehicle loads has resulted in more stringent quality requirements for asphalt pavement [3]. Studies reveal that enhancing the mixing quality of asphalt mixtures during construction directly impacts the overall construction quality and service life of the pavement [4, 5], and asphalt mixture workability (WAM) is widely recognized as a key indicator reflecting mixing quality and construction performance [6-8].

WAM primarily refers to the uniformity of asphalt distribution, aggregate distribution, and asphalt film adhesion after mixing, as well as the fluidity and cohesiveness of the mixture [9, 10]. Poor workability can lead to pavement distresses such as rutting, shoving, cracking, raveling, and bleeding, significantly shortening pavement service life [11]. Consequently, exploring effective WAM improvement methods has become a research focus in pavement engineering

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[12-15]. Existing studies have proposed various strategies to enhance WAM: Ali et al. [16] confirmed that foamed warm mix asphalt exhibits superior workability compared to hot mix asphalt. Dong et al. [17] adjusted the powder-to-binder ratio in asphalt mortar to reduce viscosity and enhance WAM. Wang et al. [18] developed a WAM test device and verified that warm mix technology can mitigate the negative impact of temperature reduction on pavement performance by improving workability. Additionally, Hou et al. [19] used the inverse of mixing torque as a WAM evaluation index and found that warm mix additives can effectively enhance the workability of hot-mixed and warm-mixed asphalt mixtures.

While these studies have made progress in identifying WAM improvement methods, critical research gaps remain. First, most existing studies focus on verifying the effectiveness of improvement measures, but lack in-depth analysis of how these measures affect the multi-dimensional uniformity of materials (asphalt, aggregates, asphalt films) [20-23]. For instance, Vaiana et al. [24] and Mongkol et al. [25] only evaluated overall mixture uniformity, without distinguishing the independent effects on asphalt distribution, aggregate dispersion, and asphalt film coating. Second, the intrinsic mechanism linking WAM improvements to material distribution uniformity is not fully elucidated. Although Yu et al. [26] and Huang et al. [27] noted that viscosity reduction contributes to workability enhancement, they did not clarify how viscosity changes regulate the bonding force between asphalt and aggregates, nor how this affects the migration and distribution of aggregates. Third, quantitative evaluation systems for material distribution uniformity under WAM improvements are insufficient. Existing studies mostly rely on macroscopic density variations or sieve analysis [28, 29], lacking specialized indices for asphalt distribution, aggregate dispersion, and asphalt film coating uniformity, which limits accurate characterization of improvement effects [30].

To address these gaps, this study aims to systematically explore the effect of WAM improvements on material distribution uniformity and reveal the underlying mechanisms. First, two common WAM enhancement methods (mixing temperature elevation and warm mix additive modification) are adopted, with SBS-modified asphalt and basalt aggregates as research objects. Second, three specialized evaluation indices are proposed: asphalt distribution uniformity index, aggregate distribution uniformity index, and asphalt film coating uniformity index, to quantitatively characterize the uniformity of different material phases. Third, combustion furnace testing, sieve analysis, and scanning electron microscopy (SEM) are combined to analyze the impacts of workability improvements on asphalt distribution, aggregate dispersion, and asphalt film coating. Finally, correlation analysis is conducted to establish the quantitative relationship between WAM and material distribution uniformity, providing a theoretical basis for optimizing asphalt mixture mixing quality and construction performance, as shown in Figure 1.

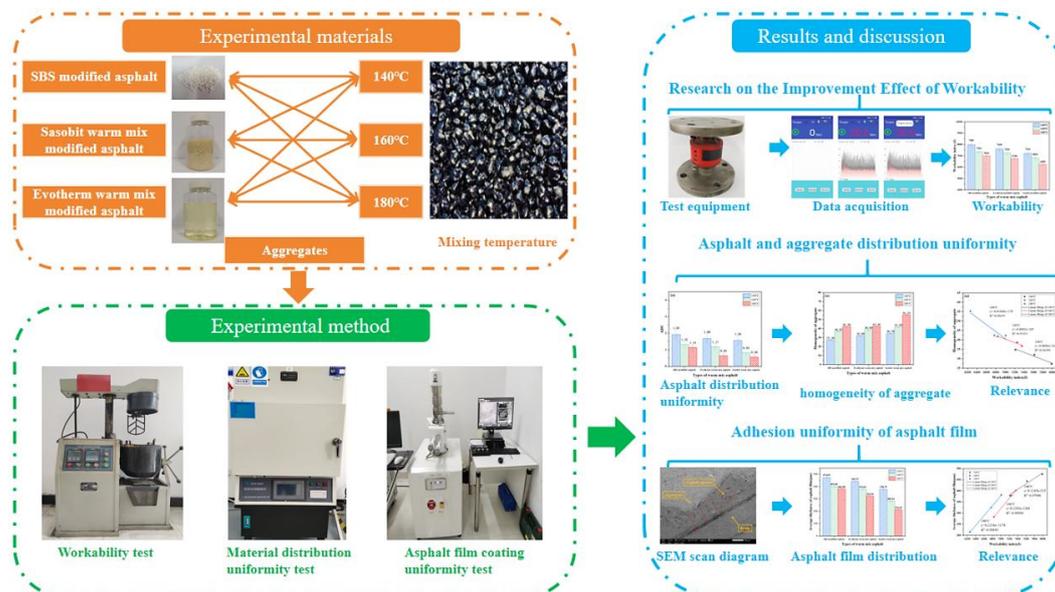


Figure 1. Research flowchart

## 2. Materials and Experimental Methods

### 2.1. Materials

#### Asphalt

In this study, high-viscosity modified asphalt was fabricated by incorporating an SBS modifier into base asphalt. Specifically, modified asphalt with a 6% Styrene-Butadiene-Styrene (SBS) dosage was selected as the test material, and this type of modified asphalt is mainly used in anti-rutting pavement construction. The properties of the modified asphalt are summarized in Table 1.

**Table 1. Characteristics of SBS asphalt**

Feature	Unit	Value	Standard
Penetration	0.1 mm	55.8	ASTM D5
Softening point	°C	54.9	ASTM D36
Ductility	cm	35.5	ASTM D100
Viscosity at 135 °C	Pa*s	2350	ASTM D4402

**Warm mix additives**

The warm mix agents used in the research are Sasobit wax-based warm mix agent and Evotherm surfactant-based warm mix agent [31]. Therefore, two types of WMAs were selected for the experiment, and their performance parameters are presented in Table 2.

**Table 2. properties of warm additives**

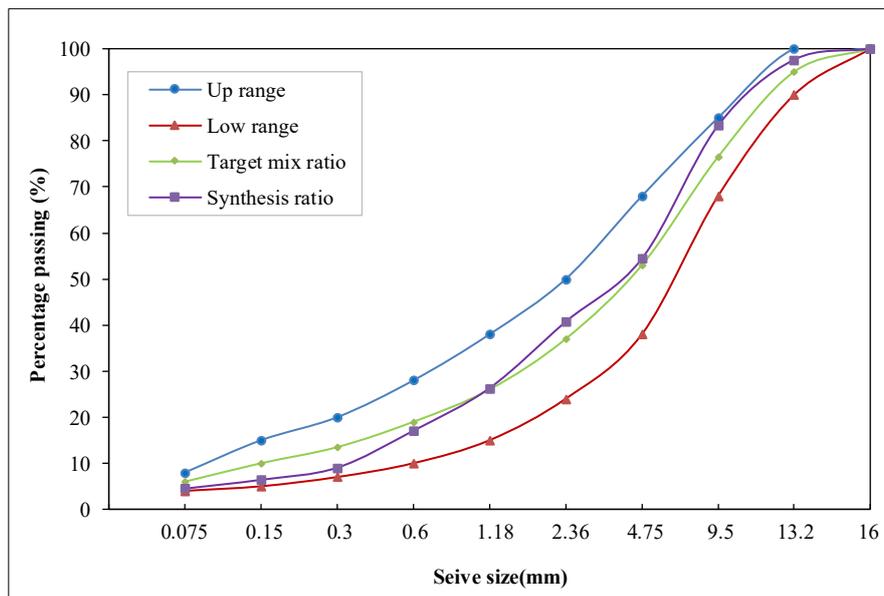
Performance	Unit	Evotherm	Sasobit
Specific gravity	-	1.02	0.65
Viscosity (25°C)	mPa*s	450-850	-
Surface tension	N/m	34.0-37.0	-
Color	-	Pale yellow	Off-white
Physical condition	-	Liquid	Solid

**Aggregates**

In this research, basalt was chosen as the aggregate, with its fundamental properties summarized in Table 3. AC-13 graded asphalt mixtures (see Figure 2) were selected as test specimens. The gradation design of these mixtures was conducted using basalt aggregates, and the deviation between the actual synthesized proportion and the target mix ratio fell within an acceptable range, achieving the desired matching effect. Specifically, the asphalt-aggregate ratio of the AC-13 mixtures was set at 4.8%.

**Table 3. The indexes and technical requirements of aggregates**

Performance	Unit	Value	Range
Water absorption	%	0.72	≤3.0
Apparent specific gravity	g/cm <sup>3</sup>	2.88	≥2.5
Needle-like content	%	11.60	≤18



**Figure 2. The test mixture gradation AC-13 is shown in the figure**

## 2.2. Experimental Methods

### Asphalt mixture workability test and evaluation

A self-developed workability testing device for asphalt mixtures was employed to measure WAM, and the schematic diagram of this device is presented in Figure 3. In engineering practice, 140 °C is the typical mixing temperature for Warm Mix Asphalt (WMA) incorporating Sasobit/Evotherm additives, 160 °C is the standard mixing temperature for SBS-modified Hot Mix Asphalt (HMA), and 180 °C represents the upper limit of mixing temperature for hot mix asphalt used in high-temperature regions or with high-viscosity mixtures. Therefore, in this study, workability indices of a total of 9 AC-13 graded asphalt mixtures were tested under three types of modified asphalt (SBS-modified asphalt, Evotherm warm mix-modified asphalt, and Sasobit warm mix-modified asphalt) and three different mixing temperatures (140°C, 160°C, and 180°C).



Figure 3. Workability test equipment schematic diagram

An evaluation index for WAM was proposed based on the minimum mixing energy consumed by the asphalt mixture from the start of mixing until it reaches uniform mixing, and this index is expressed in Formula 1:

$$E = \omega \int_0^t T dt = \omega S \quad (1)$$

here, E denotes the energy consumed by the mixture from the initiation of mixing to time t, T represents the real-time torque generated during the mixing of the asphalt mixture, t stands for the minimum time required for the asphalt mixture to achieve uniform mixing after mixing begins, S refers to the area enclosed by the torque-time curve and the time axis, and  $\omega$  is the angular velocity of the impeller during the mixing process.

### Material distribution uniformity test of asphalt mixture after mixing

WAM reflects the uniformity of material distribution, which primarily includes asphalt distribution uniformity, aggregate distribution uniformity, and asphalt film coating uniformity [32]. The distribution uniformity of asphalt and aggregates after mixing is explored by examining the distribution uniformity of materials in different positions within the mixing pot and across the upper and lower layers. The sampling method for the distribution uniformity of asphalt and aggregates at different positions is the cross evenly dividing material method (CESM), and the sampling method for the distribution uniformity of the upper and lower layers is the upper and lower four-layer sampling method (UFSM), as shown in Figure 4. During the mixing process of asphalt mixtures, vertical segregation is prone to occur due to the density difference between asphalt and aggregates. The CESM can evaluate the horizontal distribution uniformity of materials in the mixing pot, while the UFSM can reflect the vertical segregation of materials. Therefore, the simultaneous use of these two methods enables a comprehensive characterization of the three-dimensional distribution uniformity of materials. To validate the proposed workability evaluation indices, this study examined three key aspects. The test process involves dividing the mixture into four parts, and the asphalt is separated using a combustion furnace. The combustion process is conducted at 540°C for 3.5 hours. After cooling, the asphalt mixture is sieved through a standard sieve to measure the weight of aggregates with different particle sizes. Additionally, the weight loss of asphalt in the mixture before and after combustion is analyzed to assess material distribution.

#### (1) Asphalt distribution uniformity test

After preparing the nine resulting asphalt mixture groups, the asphalt content in each mixture was measured via the combustion method, following the test procedure outlined in Figure 4, this measurement data was then used to analyze the asphalt distribution uniformity within the mixtures. Notably, better asphalt distribution uniformity corresponds to a smaller asphalt distribution uniformity index (ADU). The calculation formula is as follows:

$$ADU = \frac{(A_1 - A_0)^2 + (A_2 - A_0)^2 + (A_3 - A_0)^2 + (A_4 - A_0)^2}{4} \tag{2}$$

among these parameters, ADU represents the asphalt distribution uniformity index;  $A_0$  denotes the designed asphalt content of the asphalt mixture during production, while  $A_1, A_2, A_3,$  and  $A_4$  refer to the measured asphalt contents obtained from the four layers of the asphalt mixture, respectively.

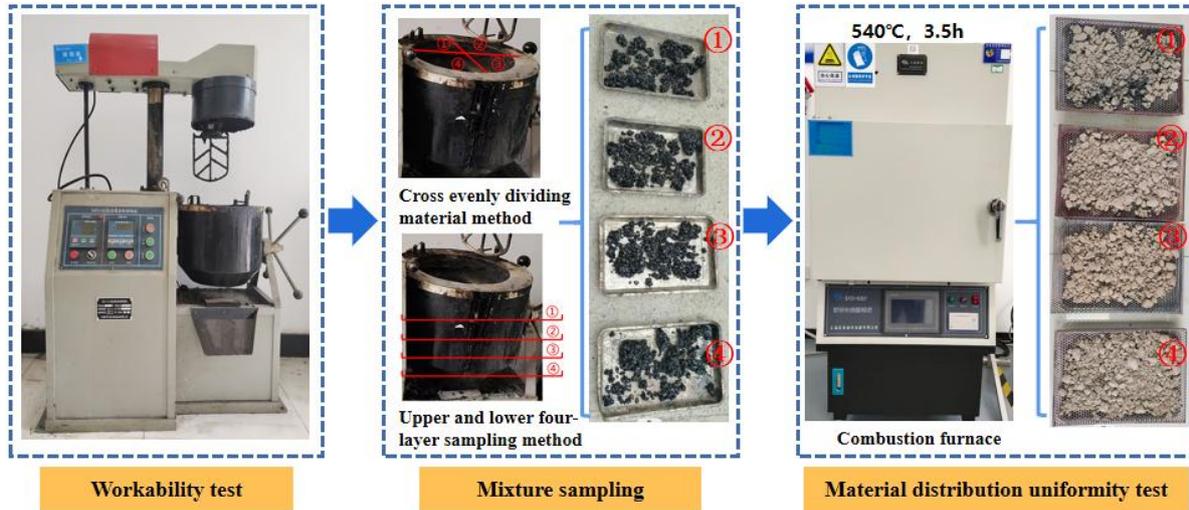


Figure 4. Flow chart of homogenization by combustion material distribution

**(2) Aggregate distribution uniformity test**

The aggregate distribution uniformity index is a key metric for evaluating the WAM. To assess how workability improvements affect asphalt mixture performance, this index was adopted to analyze the efficacy of such enhancements. In this study, after asphalt was completely burned off (ensuring uniform asphalt removal), the remaining aggregates were tested. the formula for the aggregate dispersion index (DDA) is provided below:

$$DDA = \sum_{0.075}^{19} (H_{0.075} - h_{0.075})^2 + (H_{0.15} - h_{0.15})^2 + \dots + (H_{19} - h_{19})^2 \tag{3}$$

among these,  $DDA$  is an indicator of aggregate dispersion in each layer,  $H_n$  is the passing percentage of aggregate sieve in each layer,  $h_n$  is the sieve passing percentage of aggregate production ratio.

The aggregate distribution uniformity index ( $HA$ ) formula is as follows:

$$HA = \frac{DDA_1 + DDA_2 + DDA_3 + DDA_4}{4} \tag{4}$$

among these parameters,  $HA$  stands for the aggregate distribution uniformity index, while  $DDA_1, DDA_2, DDA_3,$  and  $DDA_4$  represent the aggregate dispersion degree indexes corresponding to each of the four layers, respectively.

**(3) Asphalt film coating uniformity test**

Asphalt coating uniformity is a key index for evaluating the mixing uniformity of asphalt mixtures. In this section, the uniformity of asphalt film coating was used to investigate the efficacy of workability improvements in asphalt mixtures [33]. From these mixtures, larger-sized aggregate particles were selected to measure the thickness of the asphalt film adhering to their surfaces post-mixing, which in turn enabled analysis of asphalt film uniformity. The flowchart for testing the adhesion uniformity of the asphalt film is presented in Figure 5.

In the process of research, 20 aggregates with larger particles were taken from each pot, and the film thickness at different positions of aggregates was tested, respectively, and the average thickness was obtained using the following expression:

$$ATAF = \frac{\sum_{1}^n AF_1 + AF_2 + \dots + AF_n}{n} \tag{5}$$

among them,  $ATAF$  = the average film thickness (um), while  $AF_i$  = the thickness on the  $i^{th}$  aggregate surface (um).

According to the situation of asphalt on the aggregate surface, the adhesion uniformity of asphalt film (AUAF) is defined. The formula is as follows:

$$AUAF = \frac{\sum_1^n (AF_1 - ATAF)^2 + (AF_2 - ATAF)^2 + \dots + (AF_n - ATAF)^2}{n} \tag{6}$$

among these parameters, AUAF represents the asphalt film coating uniformity index.  $AF_1, AF_2, \dots, AF_n$  is the thickness of asphalt film on the aggregate surface.

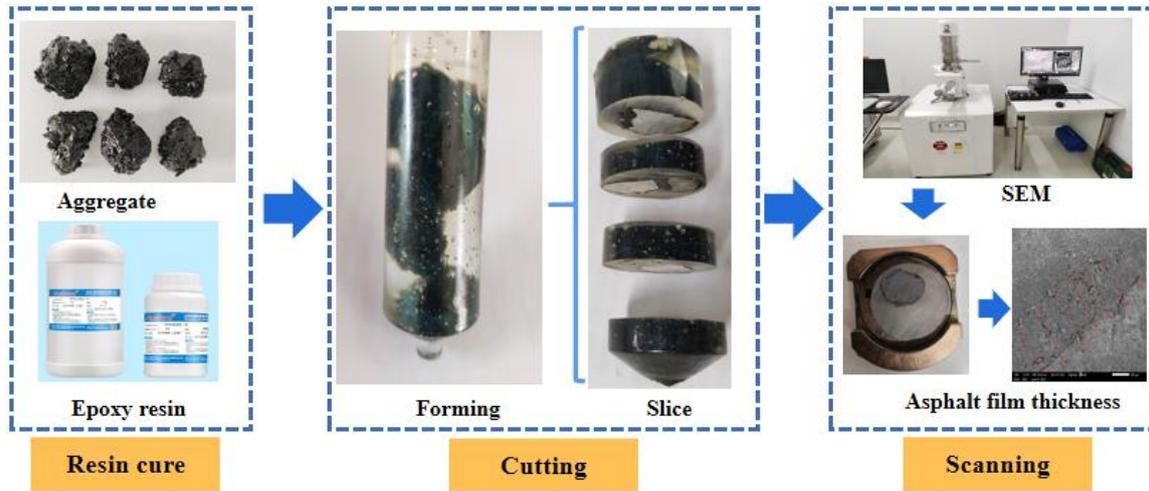


Figure 5. Asphalt membrane specimen preparation flow chart

### 3. Results and Discussion

#### 3.1. Improvement Effect of WAM

Figure 6 depicts the variation in WAM under different mixing temperatures. When comparing the WAM of the two warm mix asphalt mixtures with that of SBS-modified asphalt, it is evident that the workability index is lower for the warm mix formulations, with the Sasobit-modified asphalt mixture exhibiting the most significant reduction. This finding suggests that warm mix technology can decrease the energy consumption associated with the mixing process, as asphalt modified with warm mix additives contributes to enhanced WAM. As the mixing temperature rises from 140°C to 180°C, WAM can be improved by up to 13%. Furthermore, the incorporation of Sasobit warm mix additive can boost the workability index by a maximum of 10%. This viscosity decrease weakens the bonding force between asphalt and aggregates during mixing, thereby lowering the energy required to achieve a uniformly mixed asphalt mixture and ultimately improving workability. At the same time, with the review of the mixing temperature, the difference between the parallel tests gradually decreases, which also shows that the mixing temperature increases, the asphalt mixture is easier to mix evenly, and the energy consumption of the mixing uniformity is reduced. Consequently, it can be inferred that the application of Sasobit and Evotherm warm mix additives constitutes an effective method for enhancing WAM.

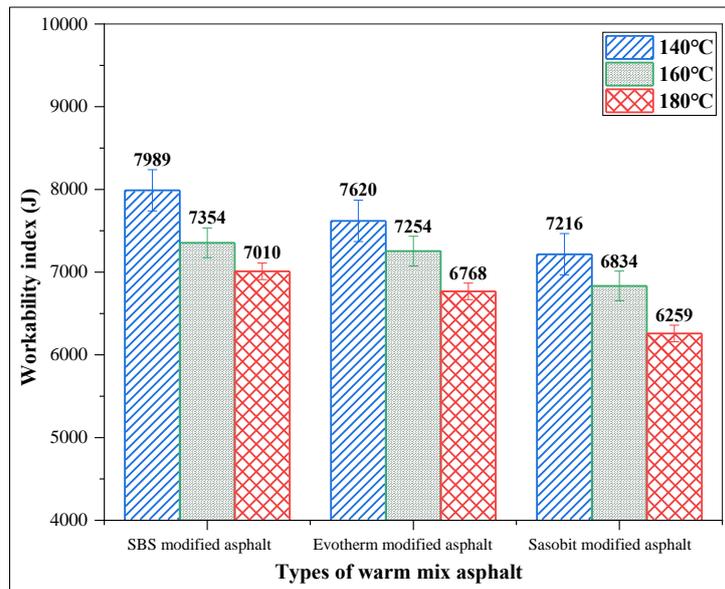


Figure 6. Workability index variation from three types of modified asphalt mixtures in three mixing temperatures

### 3.2. Effects of Workability Improvement on ADU

#### *Analysis of asphalt distribution difference in asphalt mixture*

Tables 4 and 5 present the variations in asphalt distribution across four selected asphalt mixture groups, evaluated using CESM and UFSM, respectively. As shown in Table 4, there is a small difference in the asphalt content of mixtures sampled by CESM, indicating that the distribution of asphalt in different directions of the mixing pot is relatively uniform. In contrast, Table 5 reveals a significant difference in asphalt content among samples collected from the top to bottom layers using UFSM: the asphalt content increases gradually from Sample No. 1 to No. 4, suggesting uneven asphalt distribution between the upper and lower layers of the mixture. Specifically, the upper layer contains a lower asphalt content, while the lower layer has a higher one [34]. This uneven distribution may be attributed to the high fluidity of asphalt at elevated mixing temperatures. During mixing, driven by both the motion of the mixing paddle and its own weight, the asphalt flows through the gaps between aggregates and eventually accumulates at the bottom of the mixing pot, leading to a higher asphalt content in the lower portion of the mixture.

**Table 4. Research on the distribution of asphalt (CESM)**

Temperature	Type of modified asphalt mixture	1	2	3	4
140°C	SBS	6.15	6.16	6.00	6.41
	Evothem	6.11	5.99	6.25	6.02
	Sasobit	6.22	6.06	6.15	5.70
160°C	SBS	6.31	5.58	6.02	5.76
	Evothem	5.99	5.83	5.73	5.96
	Sasobit	5.69	5.66	5.23	6.06
180°C	SBS	4.96	6.15	6.06	5.87
	Evothem	5.84	5.66	5.41	5.43
	Sasobit	5.30	5.73	5.67	5.40

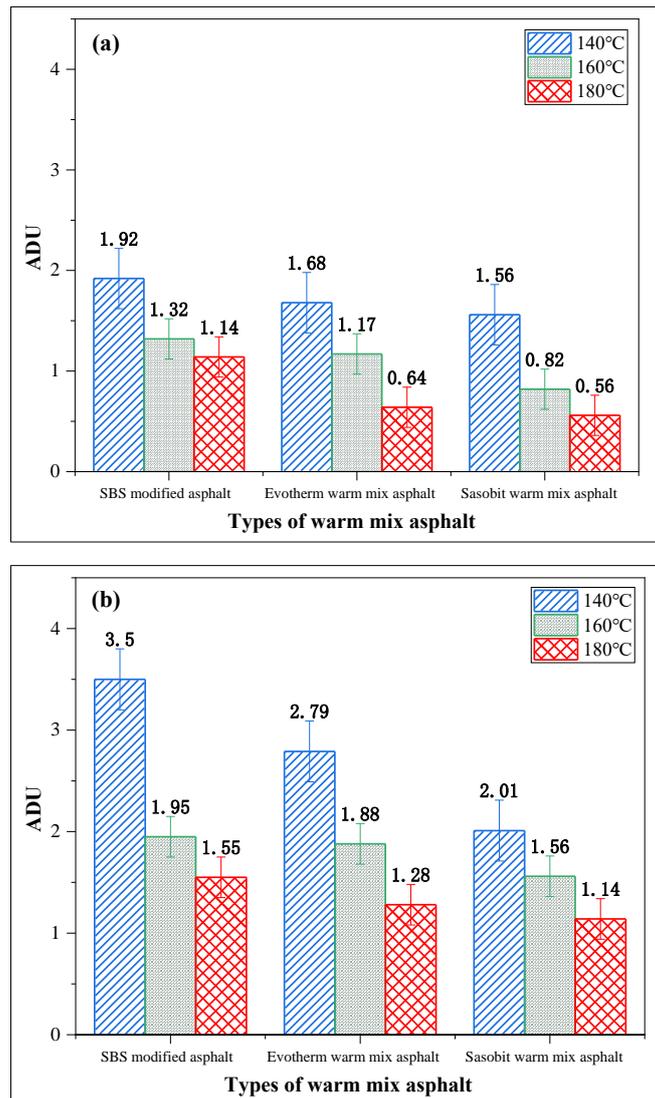
**Table 5. Research on the distribution of asphalt (UFSM)**

Temperature	Type of modified asphalt mixture	1	2	3	4
140°C	SBS	6.36	6.42	6.49	7.27
	Evothem	5.90	6.38	6.69	6.77
	Sasobit	5.96	5.97	6.39	6.47
160°C	SBS	5.80	6.15	6.36	6.39
	Evothem	5.95	6.15	6.20	6.35
	Sasobit	5.68	6.02	6.18	6.25
180°C	SBS	5.74	6.00	6.19	6.19
	Evothem	5.59	5.81	5.96	6.27
	Sasobit	5.44	5.90	5.98	6.05

A comparative analysis of Tables 4 and 5 shows that the variation in asphalt content of mixtures sampled via CESM is smaller than that of mixtures obtained through UFSM. Furthermore, increasing the mixing temperature gradually reduces the variation in asphalt distribution within the mixture. This phenomenon may stem from the enhanced fluidity of asphalt at higher temperatures, which facilitates a more uniform distribution. Adding warm mix agent can reduce the asphalt content in the mixture, especially Sasobit warm mix agent. This result suggests that warm mix technology contributes to enhanced uniformity of asphalt distribution. An investigation into how warm mix additives and high mixing temperatures affect asphalt distribution differences reveals that both measures can improve ADU, in turn enhancing the WAM.

**Research on uniformity of asphalt distribution in mixing process**

Figure 7 presents the ADU for various asphalt mixtures, showing that as the mixing temperature increases, this uniformity index decreases across all asphalt mixture types. This reduction is attributed to the fact that higher mixing temperatures lower asphalt viscosity, which in turn weakens the bonding force between asphalt and aggregates. This makes it easier for asphalt to disperse evenly among aggregates, ultimately leading to a decrease in the ADU [35]. The addition of warm mix agent can reduce the ADU in the mixture. This result confirms that warm mix technology contributes to improved ADU. Specifically, Figure 7(a) indicates that the application of warm mix additives reduces the ADU by 50.87%. In contrast, Figure 7(b) shows that warm mix additives decrease the ADU (between UFSM) by 42.57%, and a temperature increase from 140°C to 180°C results in a 55.71% reduction in this interlayer uniformity index. A comparative analysis of Figure 7 reveals that the ADU obtained via UFSM is significantly higher than that from CESM. This finding illustrates that while asphalt is distributed more uniformly across different horizontal directions in the mixing pot, its distribution between the upper and lower layers remains relatively uneven.



**Figure 7. Uniformity of asphalt distribution, (a) CESM; (b) UFSM**

**Correlation analysis of ADU and workability**

Figure 8 depicts how improvements in WAM affect ADU. The graph reveals a strong correlation between WAM and ADU: the coefficient of determination ( $R^2$ ) ranges from a maximum of 0.9999 to a minimum of 0.83493, confirming that WAM exerts a significant influence on ADU. As the workability index increases, ADU also rises; however, this correlation weakens slightly at higher mixing temperatures. The underlying mechanism is that a higher workability index indicates easier mixing, which promotes more uniform asphalt distribution and thus reduces ADU. In summary, enhancing WAM facilitates improvements in asphalt distribution uniformity. Specifically, the use of warm mix additives and increased mixing temperatures both contribute to better WAM, which in turn promotes more uniform asphalt distribution within the mixture.

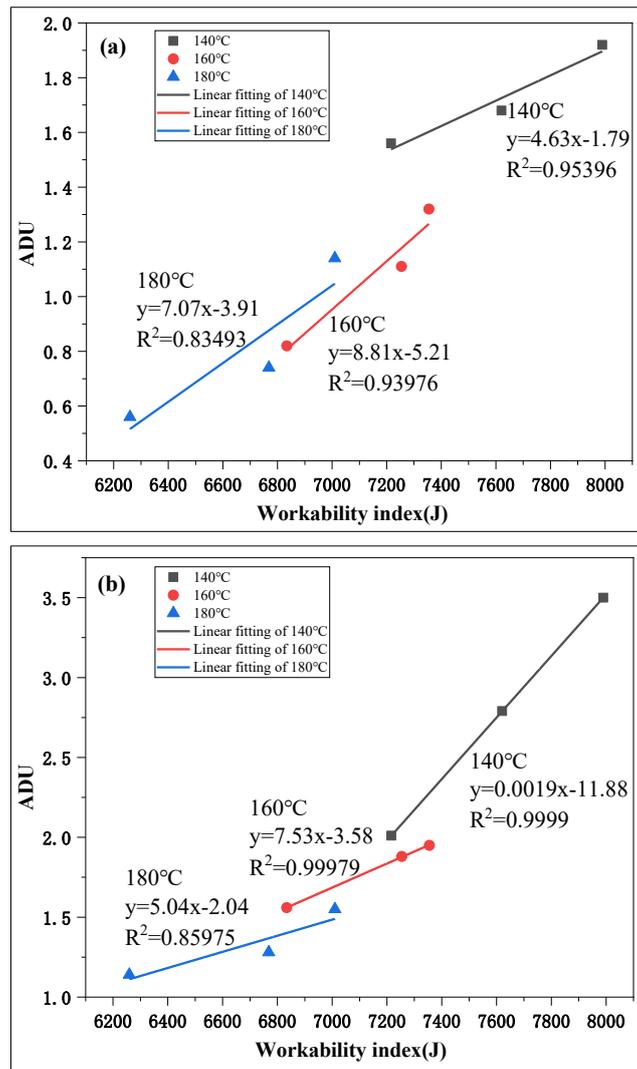


Figure 8. Effect of improved workability index on ADU (ADU), (a) CESM; (b) UFSM

### 3.3. Effect of Workability Improvement on Aggregate Distribution Uniformity

#### Analysis of aggregate dispersion

The dispersion degree of aggregates in asphalt mixtures reflects the uniformity of aggregates with different particle sizes in the final graded mixture after mixing. Tables 6 and 7 show the test results of aggregate dispersion in asphalt mixtures, which were obtained via the combustion method. It can be observed that as the mixing temperature increases, the aggregate dispersion of different asphalt mixtures is enhanced. This phenomenon may be explained by the fact that higher temperatures reduce asphalt viscosity, which in turn weakens the bonding force between asphalt and aggregates. Under this condition, when aggregates are agitated by the impeller, their distribution becomes more dispersed. The adoption of warm mix technologies further improves aggregate dispersion in asphalt mixtures, with Sasobit exhibiting a more significant effect.

Table 6. Analysis of the degree of aggregate dispersion in asphalt mixtures (CESM)

Temperature	Type of modified asphalt mixture	1	2	3	4
140°C	SBS	23.14	34.34	24.08	27.46
	Evotherm	27.14	28.35	46.13	27.54
	Sasobit	38.67	42.10	27.81	30.48
160°C	SBS	32.35	36.68	28.35	53.30
	Evotherm	35.16	34.71	26.76	58.12
	Sasobit	49.10	17.06	51.93	49.22
180°C	SBS	41.65	57.42	35.93	34.12
	Evotherm	40.85	36.23	37.31	55.13
	Sasobit	65.90	41.41	54.27	59.32

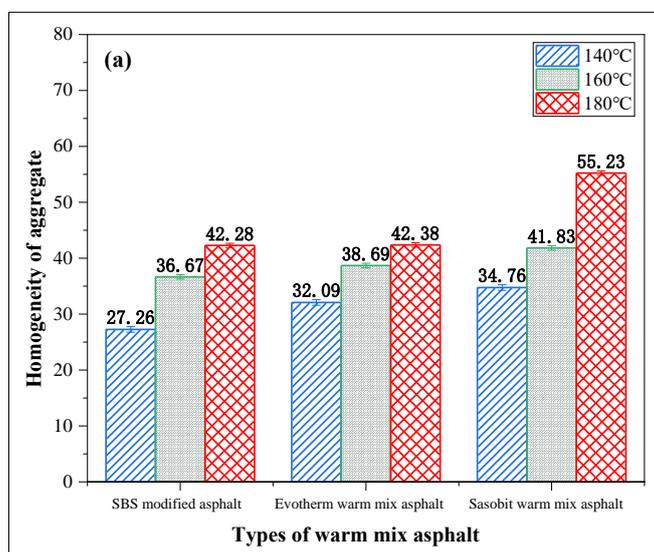
**Table 7. Analysis of the degree of aggregate dispersion in asphalt mixtures (UFSM)**

Temperature	Type of modified asphalt mixture	1	2	3	4
140°C	SBS	43.03	23.97	22.01	36.68
	Evotherm	39.95	23.61	26.40	41.81
	Sasobit	42.91	31.29	19.27	58.82
160°C	SBS	46.54	40.48	31.35	58.39
	Evotherm	69.90	33.05	30.74	48.94
	Sasobit	54.35	29.75	34.95	65.46
180°C	SBS	49.97	29.89	45.48	69.90
	Evotherm	81.12	40.48	53.01	57.76
	Sasobit	77.30	40.58	28.09	91.75

Table 6 reveals that the four asphalt mixtures selected using CESM exhibit minor variations in aggregate dispersion, with no clear pattern emerging. This indicates that after mixing, aggregates of different particle sizes exhibit some degree of distribution in various directions within the mixing pot, but the overall level of dispersion is not particularly pronounced. In contrast, Table 7 highlights significant differences in the degree of aggregate dispersion among the four asphalt mixtures selected using UFSM. Notably, the aggregate dispersion in the No.1 and No.4 asphalt mixtures is markedly higher than in the No.2 and No.3 mixtures. This suggests that after mixing, aggregates of different particle sizes become more segregated between the upper and lower layers of the mixing pot [36]. Under the influence of the mixing paddles, smaller aggregates tend to migrate toward the bottom of the pot through the gaps between larger aggregates, due to their lighter weight. Meanwhile, the larger aggregates obstruct the downward movement of finer particles, reducing their migration speed. As a result, the upper and lower layers in the mixing pot exhibit a noticeable degree of aggregate segregation.

**Research on the uniformity of aggregate distribution**

Figure 9 presents the aggregate distribution uniformity of the mixtures as measured via two distinct sampling methods, and both methods reveal a consistent trend: higher mixing temperatures correspond to better aggregate distribution uniformity. Furthermore, at the same mixing temperature, the aggregate distribution uniformity of warm mix-modified asphalt mixtures outperforms that of SBS-modified asphalt mixtures [37]. This enhancement can be attributed to the synergistic effect of warm mix additives and elevated mixing temperatures, as both factors reduce asphalt viscosity. Lowered viscosity weakens the bonding force between asphalt and aggregates, enabling aggregates to move more freely within the mixture and thus improving their overall distribution, which ultimately leads to an increase in the aggregate distribution uniformity index. Specifically, Figure 9(a) shows that the incorporation of warm mix additives increases the aggregate distribution uniformity index by 30.62%, while raising the mixing temperature from 140°C to 180°C results in a 58.87% rise in this index. Similarly, Figure 9(b) indicates that warm mix additives contribute to a 21.75% increase in the uniformity index, and a temperature increase from 140°C to 180°C further improves this index by 76.34%.



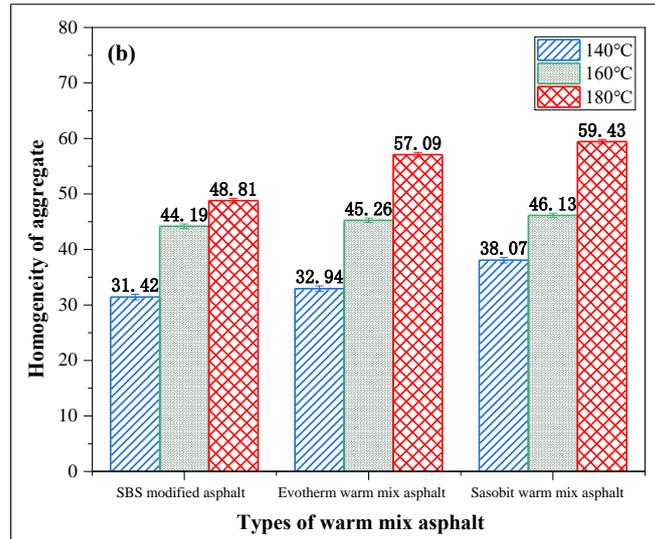
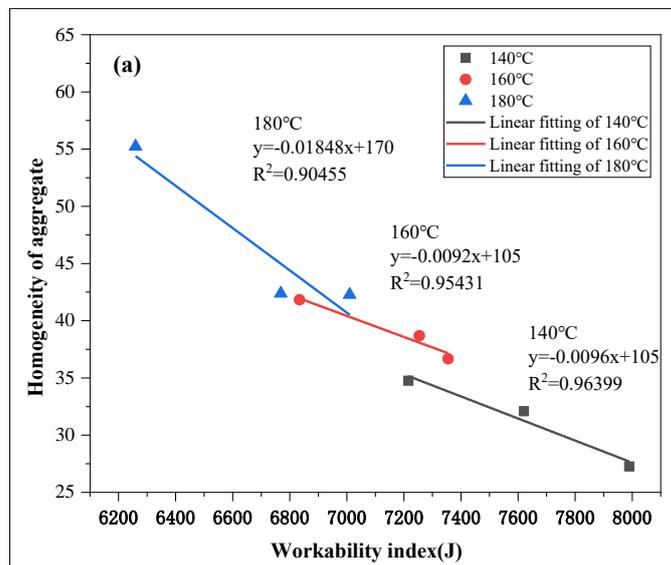


Figure 9. Uniform distribution of aggregates in asphalt mixtures: (a) CESM; (b) UFSM

A comparative analysis of Figure 9 shows that the aggregate distribution uniformity sampled via UFSM is significantly higher than that of mixtures obtained through CESM. This finding indicates that segregation between the upper and lower layers of the mixing pot is more prominent, whereas segregation across different directions within the pot is relatively mild. From a broader standpoint, this observation suggests that neither warm mix technology nor increased mixing temperature is particularly effective in enhancing the aggregate distribution uniformity of asphalt mixtures. In contrast, previous studies have confirmed that these two approaches can improve the uniformity of asphalt distribution within the mixture. Therefore, in practical construction projects, striking a critical balance is essential: while improving the WAM is important, the uniformity of aggregate distribution should not be neglected solely for the sake of achieving better workability [38].

**Research on the influence of workability improvement on aggregate distribution uniformity**

The diagrams reveal a strong association between workability and aggregate distribution uniformity, with the coefficient of determination ( $R^2$ ) ranging from 0.75728 to 0.96399. As the workability index increases, the aggregate distribution uniformity index decreases, indicating that improved workability exerts a negative impact on aggregate distribution uniformity. A comparative analysis of Figure 10 further indicates that the correlation between the aggregate distribution uniformity index and WAM is weaker for samples collected via CESM than for those obtained through UFSM. This suggests that enhancing WAM primarily affects the uniformity of aggregate distribution across different directions within the mixing pot, while exerting a lesser impact on the upper and lower layers. In summary, improving WAM does not facilitate the uniformity of aggregate distribution. Technologies such as the application of warm mix additives and the increase of mixing temperature can enhance workability, but they simultaneously reduce the uniformity of aggregate distribution within the mixture [39].



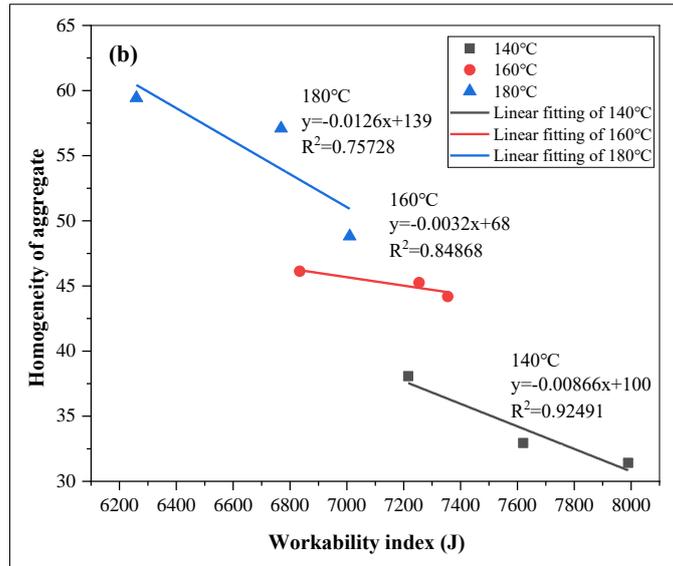


Figure 10. Effect of improved workability on uniform aggregate distribution, (a) CESM; (b) UFSM

### 3.4. Effect of Workability Improvement on the AUAF

The SEM scanning results, presented in Figure 11, demonstrate the variations in asphalt film thickness across different types of asphalt mixtures. These SEM images primarily visualize the microstructures of three components: aggregates, asphalt films, and resin. The asphalt film lies between the aggregate and the resin, with distinct differences in thickness observed. Since analyzing the uniformity of asphalt film coating through macroscopic images is insufficiently precise, this study employs the asphalt film uniformity index to quantify the coating's consistency. This approach allows for a more accurate investigation into how improved WAM affects the uniformity of asphalt film coating.

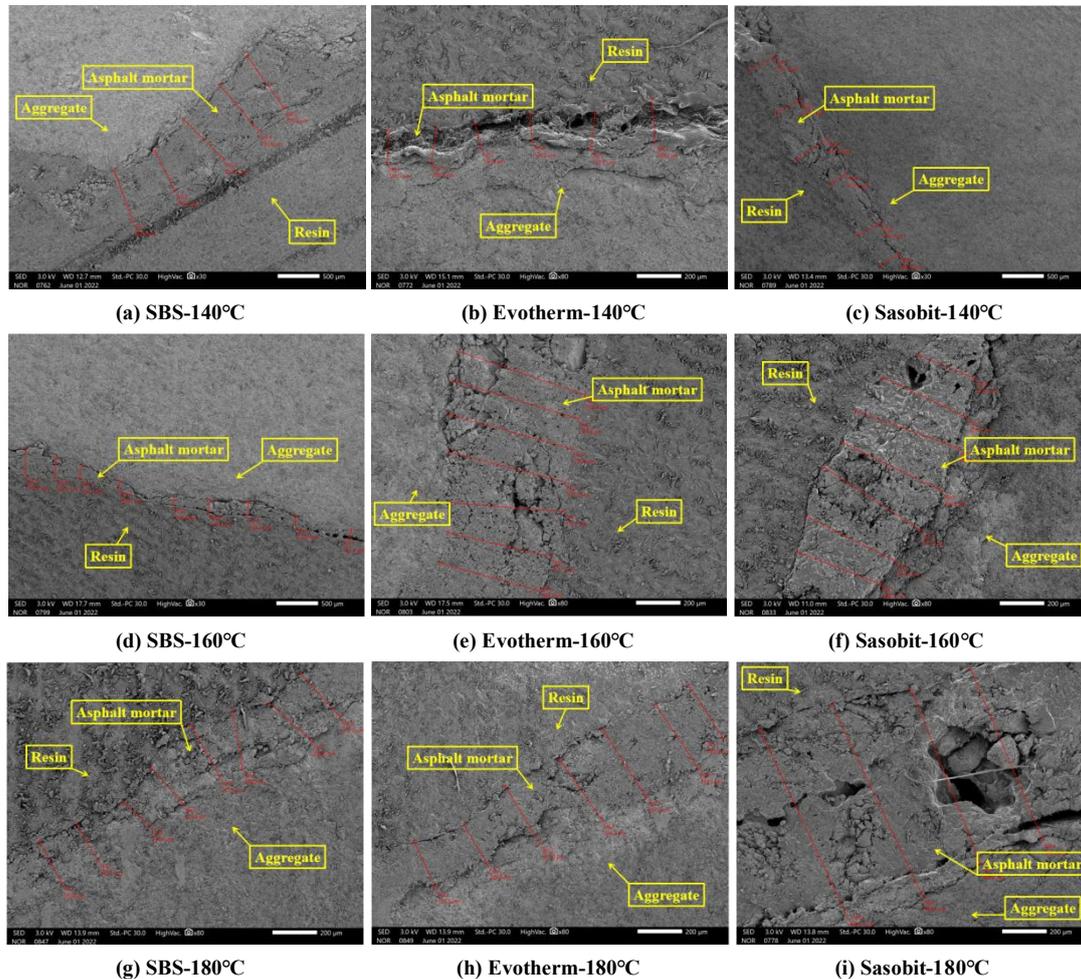
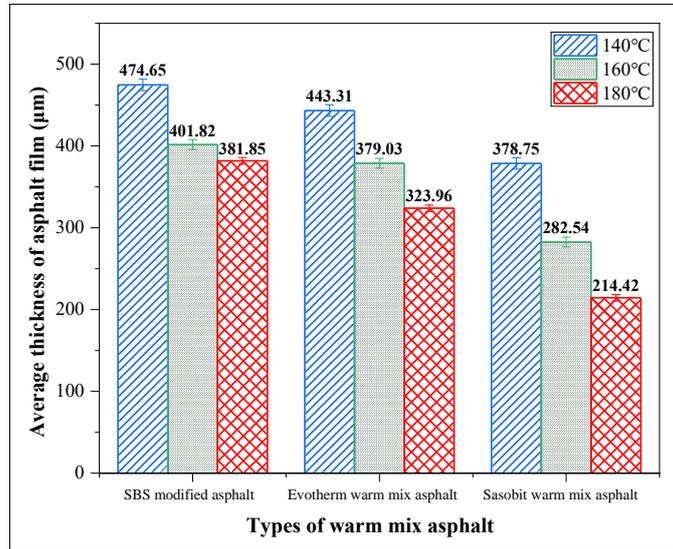


Figure 11. Asphalt SEM image of aggregate surface

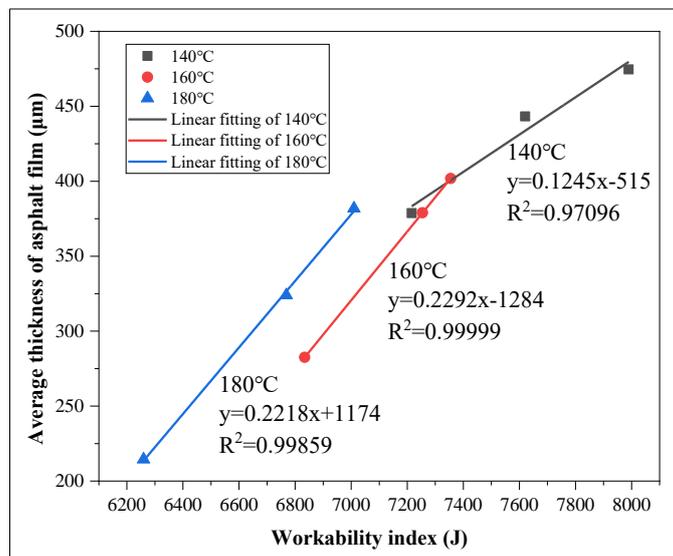
**Correlation analysis between workability and thickness of asphalt film**

Figure 12 presents the variations in average asphalt film thickness. The average asphalt film thickness decreases as the mixing temperature increases. Furthermore, at the same mixing temperature, the average asphalt film thickness of warm mix modified asphalt mixtures is significantly thinner than that of SBS modified asphalt mixtures. This difference mainly stems from the combined effects of warm mix additives and elevated mixing temperatures: both factors reduce asphalt viscosity and enhance its fluidity during the mixing process. As a result, asphalt exhibits greater mobility on aggregate surfaces, which reduces the amount of asphalt adhering to and coating the aggregates, ultimately leading to a lower measured asphalt film thickness in these mixtures [40].



**Figure 12. Average thickness disparity of asphalt film coated on aggregate surface**

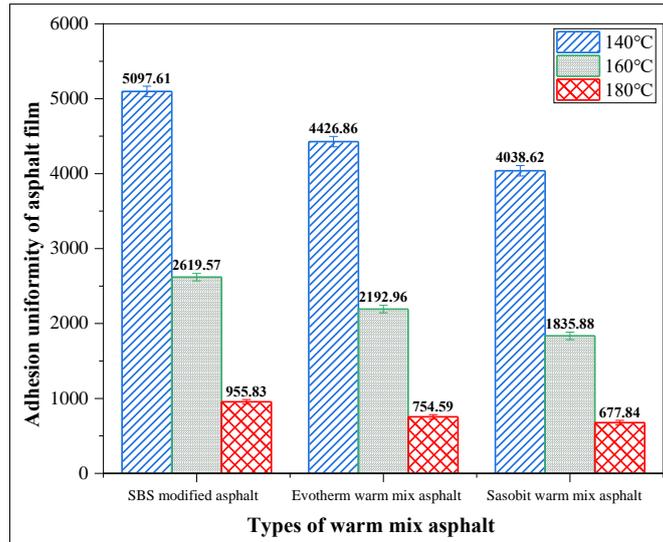
The relationship between the workability and the average thickness of the asphalt film is shown in Figure 13. The figure reveals a strong relationship between these two parameters: at different mixing temperatures, the coefficients of determination ( $R^2$ ) reach 0.9999, 0.9986, and 0.9709, respectively. This confirms that the WAM exerts a significant influence on the average thickness of the asphalt film coating aggregate surfaces. In the tests, the incorporation of warm mix additives and the use of elevated mixing temperatures modified the WAM by altering asphalt viscosity. Notably, the uniformity of asphalt coating on aggregate surfaces is also closely associated with asphalt viscosity, this establishes a strong link between the WAM and the uniformity of asphalt film coating. Furthermore, a higher WAM corresponds to a greater average thickness of the asphalt film. This phenomenon can be explained as follows: improved workability reduces the uniformity of mixture blending, which in turn diminishes the fluidity of asphalt on aggregate surfaces. After mixing, this leads to increased asphalt accumulation on the surfaces of coarse aggregates, ultimately resulting in a thicker asphalt film.



**Figure 13. Effect of improved workability on the thickness of asphalt film**

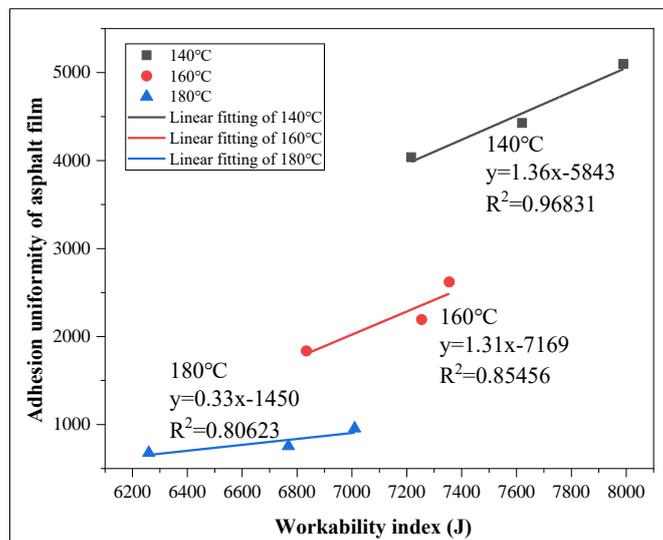
**The relationship between the adhesion uniformity and the workability of asphalt film**

The data show that higher mixing temperatures are associated with a lower uniformity index of the asphalt coating on aggregate surfaces. Additionally, the adoption of warm mix technology also contributes to a reduction in this index. Notably, within the same type of asphalt mixture, significant differences in asphalt coating uniformity are observed at different mixing temperatures. This variation can be attributed to the fact that both warm mix technology and elevated mixing temperatures reduce asphalt viscosity. Lowered viscosity enhances the fluidity of asphalt on aggregate surfaces, promoting more uniform asphalt distribution and consequently decreasing the coating uniformity index [41]. The diagram further reveals that the application of warm mix additives can reduce the uniformity index of the asphalt film in the mixture by 29.92%, as shown in Figure 14. In contrast, increasing the mixing temperature from 140°C to 180°C leads to a remarkable 83.22% decrease in the asphalt film uniformity index. Overall, this analysis indicates that while warm mix technology improves asphalt film uniformity, raising the mixing temperature exerts a more prominent effect on enhancing the uniformity of the asphalt coating on aggregate surfaces.



**Figure 14. Disparity in asphalt film coating homogenization**

Figure 15 depicts the relationship between the WAM and the adhesion uniformity index of asphalt films. A strong correlation exists between these two indices, with the maximum coefficient of determination ( $R^2$ ) reaching 0.9683. This finding indicates that as the WAM increases, the adhesion uniformity index of asphalt films also rises, showing a consistent positive correlation. Such a trend suggests that the WAM plays a critical role in determining the AUAF. Additionally, the figure reveals that the correlation between workability and the asphalt film uniformity index weakens at higher mixing temperatures. This phenomenon can be attributed to the reduced bonding force between asphalt and aggregates under elevated temperature conditions, which lessens the impact of WAM on the AUAF. Consequently, the mixing temperature exerts an influence on the strength of the correlation between these two indices. In summary, enhancing the WAM has a significant effect on the uniformity of asphalt film coating. Therefore, the adhesion uniformity of the asphalt coating on aggregate surfaces can be effectively estimated using the WAM.



**Figure 15. Correlation analysis between workability and asphalt film adhesion uniformity**

## 4. Conclusions

The primary objective of this study is to improve WAM by applying warm mix additives and increasing mixing temperatures. Additionally, it explores how these workability enhancements affect three key aspects: asphalt distribution uniformity (ADU), aggregate distribution uniformity (HA), and asphalt film adhesion uniformity (AUAF). Based on the conducted analyses and obtained results, the main conclusions are summarized as follows:

- Increasing the mixing temperature from 140°C to 180°C can enhance WAM by up to 13%. Additionally, adding Sasobit warm mix additive can further raise this workability index by a maximum of 10%.
- The variation in asphalt content within asphalt mixtures, as measured by CESM, is less notable than that observed via UFSM. When warm mix additives are used, the ADU across different directions in the mixing pot decreases by 58.87%. Furthermore, increasing the mixing temperature from 140°C to 180°C leads to a 64.1% reduction in the ADU for these multi-directional regions.
- The adoption of warm mix technology can improve the dispersion degree of aggregates in asphalt mixtures, with Sasobit-modified mixtures exhibiting more effective results. When these warm mix additives are incorporated into SBS-modified asphalt, the viscosity of the resulting warm mix-modified asphalt decreases significantly. This reduction in viscosity diminishes the bonding between asphalt and aggregates, in turn improving the ability of aggregates to migrate within the mixture.
- As the mixing temperature rises, the uniformity index of the asphalt film coating aggregate surfaces declines, and warm mix technology further accelerates this decrease. The use of warm mix additives can reduce the asphalt film uniformity index in asphalt mixtures by up to 29.92%. By contrast, increasing the mixing temperature from 140°C to 180°C leads to a notable 83.22% drop in this index. It is worth noting that compared with warm mix technology, raising the mixing temperature exerts a more distinct effect on improving the uniformity of asphalt coating on aggregate surfaces.

This paper explores the feasibility of improving asphalt mixture workability (WAM) via warm mix agents and elevated mixing temperatures and verifies the improvement effects, while acknowledging that the use of only one base asphalt (SBS-modified asphalt) and one aggregate (basalt) may limit result generalizability—nevertheless, polymer-modified asphalts with similar viscosity are expected to respond consistently to temperature and warm mix additives, and aggregates with higher porosity may slightly weaken the impact of workability improvement on asphalt film uniformity without altering the overall correlation between workability and material distribution uniformity; future research should further investigate the intrinsic mechanisms of WAM improvement, develop workability enhancement approaches for plant-mixed recycled asphalt mixtures to promote recycled material application, and expand material types to validate conclusion universality and provide comprehensive engineering technical support.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, G.D. and B.C.; methodology, B.C.; software, H.Z.; validation, B.C., G.D., and H.Z.; formal analysis, B.C.; investigation, C.T.; resources, B.C.; data curation, C.T.; writing—original draft preparation, C.T.; writing—review and editing, B.C.; visualization, G.D.; supervision, H.Z.; project administration, B.C.; funding acquisition, G.D. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

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