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Analysis of Fume Enrichment Methods and Release Patterns of Plant-Mixed Asphalt Mixtures

Tengfei Nian*, Jiaqi Song, Jinggao Li, Ping Li, Xiule Chen

(School of Civil Engineering, Lanzhou university of technology, Lanzhou, Gansu 730050, China)

Abstract: The disorderly emission and poor treatment effect of asphalt mixture fume in asphalt mixing stations have caused huge harm to the natural environment and human health. Based on the gravimetric method, self-designed and assembled fume generation-enrichment device that was suitable for the mixing state of asphalt mixture in the plant, and conducts research on the fume release rules during asphalt mixture mixing. Four kinds of petroleum asphalt were selected to consider the conditions of asphalt fume generation in the field mixing station. The mixing temperature, aggregate specific surface area and mixing frequency were determined as the key factors affecting the release of fume. The exposed area of the aggregate was calculated by the measured modified specific surface area calculation method, and the influence of each key factor on the smoke release of the plant-mixed asphalt mixture was analyzed. The results show that the self-designed and assembled fume generation-enrichment device has good stability and can ensure the accuracy of the experimental results. The magnitude of the light components in the fume under different mixing conditions is much lower than that of the heavy components, and the fume release after the base asphalt is modified by SBS is reduced. Mixing temperature is the most critical factor that determines the amount of fume release. The amount of fume release shows an obvious growth trend with the increase in temperature. Fume production has strong temperature sensitivity, and release varies significantly under different mixing temperatures. 160 ℃ and 170 ℃ are the jumping nodes of fume release. The amount of fume produced by the asphalt mixture is directly proportional to the specific surface area of the aggregate. The specific surface area of the aggregate directly affects the amount of fume released by determining the exposed area of the asphalt. The amount of fume release is positively related to the mixing frequency. Compared with the heavy components of the fume, the release amount of the light components of the fume is less affected by the mixing frequency. The research results can provide theoretical and technical support for the release and disposal of fume in mixing plants.

Key words: road engineering; enrichment device; weight method; asphalt fume; fume release rules

1 Introduction

Asphalt, the main raw material of highway construction, is typically combined with aggregate to form asphalt mixture for paving and road surface maintenance. However, during production, storage, and use, asphalt fumes are generated due to high temperature conditions and natural factors. These fumes primarily consist of volatile organic compounds (VOCs). suspended in the air as aerosols[1]. The main harmful component in asphalt fumes is polycyclic aromatic hydrocarbons (PAHs). The relevant studies of the International Agency for Research on Cancer pointed out that the number of aromatic rings is a key indicator to measure the harm of fume[2], and PAHs with more than 2 rings are irritating and carcinogenic. In addition, LI, et al.[3] also found that not only PAHs in asphalt fume has carcinogenic effect, but also some heterocyclic hydrocarbons containing oxygen and nitrogen have certain carcinogenic effect. Asphalt smoke causes harm to human body mainly by stimulating human skin and respiratory system, and the representation of carcinogens in employees exposed to asphalt smoke for a long time is much higher than normal[4-6]. At the same time, asphalt smoke will also cause serious damage to the ecological environment, and the smoke suspended in the air will fall to the ground along with rain and fine dust, causing water and soil pollution[7].

Currently, there is no uniform method and standard for the enrichment of asphalt fume at home and abroad, which usually adopts two forms of on-site enrichment and laboratory enrichment. Because the asphalt fume is suspended in the air in the form of aerosol under high tem-

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* *E-mail address*: tengfeinian@lut.edu.cn

perature conditions, affected by external environmental factors, the fume presents a disorderly diffusion state, and it is easy to adhere to the surface of low-temperature objects and form a colloidal solid, so it is difficult to enrich on site. The variable factors in the laboratory test are highly controllable, the equipment is complete and the instrument is operable, which can realize the direct detection of asphalt smoke. Therefore, when carrying out relevant research, scholars mostly prepare and enrich asphalt smoke in the laboratory. XU, et al. [8] used a microporous PTFE filter membrane to adsorb asphalt fume and built a self-made laboratory asphalt smoke collection device based on the weight method, and explored the influence of factors such as asphalt type, heating temperature and heating time on the fume release. HUANG, et al. [9] selected polypropylene fiber cotton from five adsorption materials to adsorb asphalt fume in order to explore the influencing factors of asphalt smoke release. According to the physical adsorption principle and characteristics of the fume, an integrated asphalt fume enrichment system was developed based on the quality method. LI, et al. [10-11] designed laboratory tests, using conical flask as the fume generating device and polypropylene fiber as the adsorption material, and finally realized the enrichment of asphalt fume at different heating temperatures.

In terms of the concentration of asphalt mixture fume, PARANHOS, et al. [12-13] installed asphalt smoke sampling equipment with PAHs and organic compound sampling probe on the laboratory mixing machine, and used a portable hydrocarbon automatic detector to sample and analyze the hot mixed asphalt mixture fume. ZHENG[14] also chose to install fume sampling equipment on the laboratory mixing machine to measure the fume concentration in order to explore the relationship between fume emission and mechanical properties of asphalt. Based on the mixing characteristics and paving rules of asphalt mixture, CUI[15] designed a smoke collection device for asphalt mixture for reference to the indoor smoke production test of pure asphalt. The device extracts the smoke generated during the process through the negative pressure action of vacuum pump, and finally uses chemical extraction to enrich the smoke.

There is a scarcity of researches on asphalt mixture smoke production test. Most scholars reveal the general regulation rate of smoke production of asphalt mixture through the smoke production test results of pure asphalt, which is obviously inappropriate. In the pure bitumen smoke production test, a conical bottle within 2 L (with a small base area) is usually used as the bitumen smoke generating device, and the bitumen sample placed in it is often heated for more than 2 h[10]. However, in the actual mixing production, the mixing time of the asphalt mixture is very short, usually between 45 s and 60 s, and asphalt in a film state, net the accumulation state in the conical bottle. As a result, the details of asphalt adhesion state (thickness), exposed area and working time under the test condition of pure asphalt are very different from the actual plant mixing conditions of asphalt mixture. As a result, the test results can only reveal the smoke production law of pure asphalt under different conditions, and if it is applied to the smoke production analysis of asphalt mixture in actual engineering, it is not reliable.

Given the concentrating of asphalt fumes, collection and disposal are more feasible than during the paving stage. Therefore, it is necessary to study fume release during asphalt mixture mixing to solve environmental treatment problem. This study uses asphalt mixture as the test material. By comprehensively considering the characteristics of the existing fume collection device, designing a self-made test device to simulate fume generation during factory mixing in the laboratory. By examining the effects of various mixing conditions on fume release using the weight method, in order to provide data support for the environmental treatment of asphalt mixture plant mixing buildings of the.

2 Experimental design

2.1 Raw material properties and mix ratio design

2.1.1 Asphalt

The asphalt matrix used in this study is South Korea SK-90 (hereinafter referred to as SK) and Klian KL-90 (hereinafter referred to as KL) road petroleum asphalt. SBS is used to modify the two kinds of asphalt matrix respectively to prepare SK-SBS and KL-SBS modified asphalt. According to the requirements of "Technical Specification for the Construction of Highway Asphalt

Pavement" (JTG F40—2004), the pavement performance indexes of the base asphalt and modified asphalt were tested, and all the technical indexes met the requirements of the specification. (In order to compare and analyze the changes of the base asphalt and modified asphalt before and after aging, according to the requirements of JTG F40—2004, Matrix asphalt elongation test temperature is 10 ℃, SBS modified asphalt elongation test temperature is 5 ℃). The SBS modified asphalt used in this study was prepared by wet process[16], and all technical indicators were tested according to the current specifications, and the test results showed that all basic technical indicators met the requirements of the specifications. The test results of matrix and modified asphalt technical indexes are shown in Table 1.

Table 1 Technical indexes of asphalt

Detection index		Unit	SK-90	KL-90	SK-SBS	KL-SBS
Penetration(25 ℃,5 s,100 g)		0.1 mm	82	85	63	65
Ductility (10 ℃)		cm	69	>100	45*	38*
Softening point $T_{R\&B}$		℃	46.5	48	85	87
Residue after RTFOF	Mass change	%	−0.01	−0.05	−0.07	−0.12
	Residual penetration ratio	%	65	74	68	75
	Residual ductility 10 ℃	cm	9	46	20*	25*

Note: * 5 ℃, 5 cm/min ductility.

2.1.2 Asphalt mix ratio design

The coarse and fine aggregates used in this study were all from Lintao Quarry in Dingxi, Gansu Province, and limestone was selected as the mineral powder. The needle flake content, firmness and moisture content of coarse and fine aggregate and mineral powder were tested by experiments. All the properties of aggregate and mineral powder can meet the requirements of current technical specifications. Three dense graded asphalt mixtures AC-13, AC-16 and AC-20 were selected as test objects, and the mix design was carried out according to Marshall mix design method. The grading results are shown in Figure 1. Marshall test results show that the optimum ratio of oil to stone for the three graded asphalt mixtures is 5.0%, 4.5% and 4.3%, respectively.

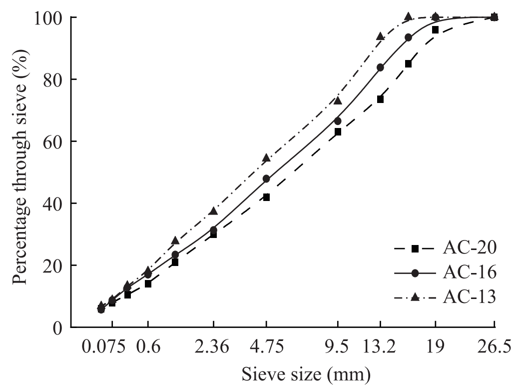


Fig. 1 Asphalt mixture gradation curves

2.2 Asphalt fume enrichment and measurement device

In this study, we independently designed and assembled a set of asphalt fume generation and enrichment equipment, which can simulate the mixing process and smoke production state of the asphalt mixture in a mixing station, and can effectively enrich the fume produced during the mixing process. The gravimetric method is used to measure the fume emission. The method has strong controllability, simple operation and can directly reflect the change of fume emission under different mixing conditions. Specific test design and methods are as follows.

2.2.1 Test device and working principle

Figure 2 shows the structure principle diagram of the self-designed and assembled bitumen mixture fume generation-enrichment device. Among them, 1 is a mixing machine; 2 is asphalt mixture; 3 is the fume enrichment port; 4 is the gas transmission pipe; 5 is the filter tube; 6 is U-shaped glass tube; 7 is the vacuum pump; 8 is a conical bottle; 9 is the absorption solution.

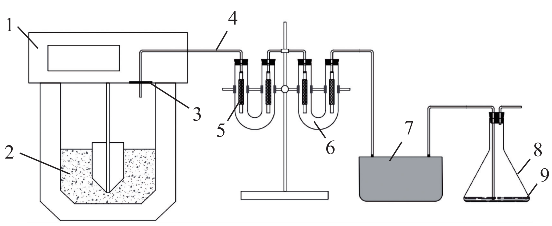
(1) Smoke generating device

The fume generating device is converted from the asphalt mixing machine used in the laboratory. The capacity of the mixing cylinder is 20 L, and the exhaust hole of the mixing cylinder is converted into the enrichment port of fume. The mixer has temperature control and insulation function, the temperature can reach 200 ℃, the power of the mixing motor is 550 W, and the initial mixing frequency of the mixer is 76 r/min.

(2) Fume enrichment device

The fume enrichment device is mainly composed of filter tube, U-shaped glass test tube, absorption bottle, gas conduit and vacuum pump. The filter tube is mainly used to enrich the fume component with a particle size greater than 2 μm (called the recombination component in this study), and the absorption bottle is responsible for enriching the fume component with a particle size less than 2 μm (called the light component in this study).

(a) Physical device diagram



(b) Device diagram

Fig. 2 Experimental device diagram

a. The filter tube used in this study is a combination of a filter membrane and a solution dropper, and the filter membrane is wrapped around a solution dropper with uniform holes. As for the selection of adsorbent filter membrane materials, this study referred to the material selection results of HUANG and ZHANG[9, 17], and selected polypropylene fiber filter membrane with strong fume adsorption capacity and good hydrophobicity to enrich the recombination of asphalt fume. The filter membrane size is 50 mm×80 mm, the model is 2#, and the aperture is 2 μm. The material of the selected solution dropper is PVC material, which has the characteristics of light weight and small volume, can capture the small mass change of the filter membrane, and meet the accuracy requirements of the quality measurement of asphalt smoke.

b. U-shaped glass test tube is connected with the filter tube through a rubber plug and covered outside the filter tube, which not only plays the role of conduit gas transmission, but also protects the filter membrane from external environment pollution.

c. Curently, ultraviolet spectrophotometry is widely used to determine the concentration of light components in asphalt smoke. This method uses the amount of solute extracted from asphalt smoke by organic solvent to represent the concentration of asphalt smoke. LI[18] found through experiments that the solubility of asphalt smoke in benzene solution is better than that of other organic solvents such as cyclohexane, and its maximum absorption peak is at the wavelength of 286 nm, which accords with Lamberbier's law and has good reproducibility. Therefore, the UV spectrophotometry method is simplified in this experiment, and the quality of light components in asphalt smoke is characterized by the good absorption performance of benzene solution to asphalt smoke. The conical bottle added with benzene solution is used as the absorption bottle of light components of fume.

d. The gas transmission between the components of the enrichment device is carried out in the gas transmission pipe, which is made of glass and rubber.

e. The vacuum pump used in the test is a constant flow pumping vacuum pump with a power of 120 W and a pumping speed of 0.5 L/s.

(3) Smoke quantitative instrument

The high-precision analytical balance is used to quantify the light and recombination components of asphalt fume. The measuring accuracy of the analytical balance is 0.000 1 g, which can ensure the detection of small mass changes.

2.2.2 Determine the number of filter tubes

In order to ensure the effective enrichment of asphalt fume recombination and avoid the waste of test materials, it is necessary to determine the number of filter tubes required for the test. AC-13 asphalt mixture (total 1.2 kg) was prepared using SK and KL asphalts, and the mixing temperature was set at 180 ℃. The recombination separation and enrichment test was carried out according to the test method in section 2.4.2. The initial number of filter tubes was set to 6 ($1^{\#}$-$6^{\#}$), and the filter tubes were numbered according to the distance from the smoke source. The number of filter tubes required for the test was determined by comparing the degree of mass change before and after the test of various filter tubes, and the test results were shown in Figure 3.

It can be seen from Figure 3 that under the two groups of test conditions, the mass of fume enriched by the primary filter tubes exceeds 70% of the total enrichment, and the mass of the first three filter tubes exceeds 97% of the total enrichment, and the mass of fume enriched by the last two filter tubes is almost 0. Therefore, the number of filter tubes used in this test is finally determined to be 4.

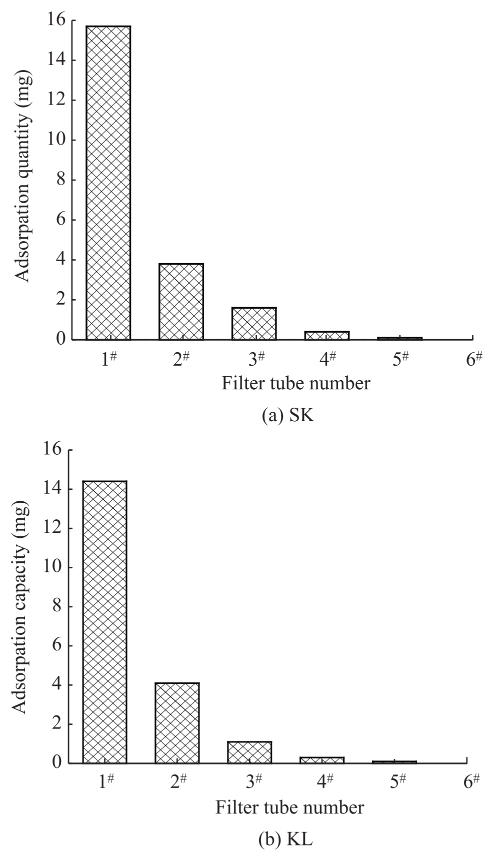


Fig. 3 Effect of the number of filter tubes on the test results

2.2.3 Device reliability test

AC-13 asphalt mixture (total 1.2 kg) was prepared with SK matrix asphalt, and the mixing temperature was set at 170 ℃. The fume enrichment was carried out according to the test method in Section 2.2. The reliability of the device was judged by comparing the total smoke production, the adsorption capacity of all levels of filter tubes ($1^{\#}$-$4^{\#}$) and the absorption liquid ($A^{\#}$) of three consecutive parallel tests. The test results are shown in Figure 4.

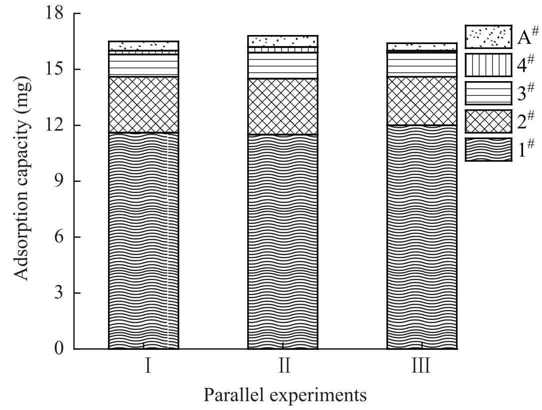


Fig. 4 Device reliability test

According to the experimental results in Figure 4, it can be seen that the total smoke production of the three parallel experiments under the same mixing condition is roughly consistent, and the fractional enrichment of each filter tube and absorption liquid is roughly the same. It can be concluded that the self-designed fume generation and enrichment device has good stability and can guarantee the accuracy of the experimental results.

2.3 Experimental method for determination of fume emission

2.3.1 Experimental conditions for fume release

The preparation of hot mix asphalt mixture requires not only reasonable selection of asphalt type and grade type, but also appropriate mixing conditions according to different raw materials and uses. These factors will not only affect the preparation quality of asphalt mixture, but also affect the emission characteristics of fume. It has been pointed out that the existence of high temperature is the prerequisite for asphalt smoke production, and the change of temperature will lead to the difference of asphalt smoke production[19], and temperature is the key factor affecting the smoke production of asphalt mixture. When the factory mixed asphalt mixture is prepared, the asphalt will form a thin film structure on the surface of the aggregate after mixing, and the thin film structure formed by the asphalt on the surface of the aggregate is the main body of a large amount of smoke during the mixing of the asphalt mixture. The exposed surface of the asphalt film constitutes the fume escape channel. If the surface area of the aggregate is approximately the exposed area of the asphalt, Therefore, the change of specific surface area of aggregate caused by different aggregate gradation composition will inevitably lead to the difference of asphalt exposed area, and thus lead to the change of smoke production of asphalt mixture[10]. According to the smoke production mechanism of asphalt mixture[20-21], the smoke mainly comes from the thermal oxidation decomposition reaction of asphalt components, so it is speculated that the concentration of oxygen is also an important factor determining the smoke production of asphalt mixture. Mixing in the mixer will increase the contact frequency of asphalt and oxygen, thus promoting the thermal oxidation escape of asphalt components[22].

The effect of mixing time on fume release was not considered in this paper because the mixing time remained basically unchanged during the preparation of plant mixed asphalt mixture. Therefore, the research idea is determined as follows: Using four representative petroleum asphalt as raw materials, the effects of mixing temperature, specific surface area of aggregate and mixing frequency on the fume release during the processing of hot mixed asphalt mixture are studied through laboratory experiments. The specific experimental design is shown in Table 2.

Table 2 Mixing condition design

Influencing factor	Parameter settings
Asphalt type	SK、SK-SBS、KL、KL-SBS
Gradation composition	AC-13, AC-16, AC-20
Mixing temperature (℃)	150, 155, 160, 165, 170, 175, 180
Mixing frequency (R/min)	38, 76

2.3.2 Calculation of specific surface area of aggregate

The specific surface area calculation method of aggregates is stipulated in China's "Technical Specification for Highway Asphalt Pavement Construction" (JTG F40—2004). The principle of the calculation method is based on the hypothesis put forward by American engineer Wim, which simplifies aggregates into spherical particles, and then calculates the specific surface area of aggregates of each particle size. At the same time, the empirical formula of aggregate specific surface area given by American Asphalt Society is introduced, see Equation (1).

$$\begin{cases} SA = \sum (P_i \times FA_i), \\ FA_i = \dfrac{C}{G_a d}, \end{cases} \tag{1}$$

where, SA is the specific surface area of aggregate; P_i is the amount of aggregate passing through each screen hole; FA_i is the modified surface area coefficient of each particle size, the value range is shown in Table 3; C is a constant; d is the size of the screen; G_a is the apparent density of aggregate.

According to the calculation of aggregate specific surface area in the specification, the size of aggregate specific surface area depends on the distribution of aggregate particle size. However, some studies have found[24-25] that the total specific surface area of aggregates calculated by the measured method and the empirical formula is quite different. The measured specific surface area value of aggregates above 0.3 mm has a small difference from that calculated by the empirical formula, while the difference of particles below 0.3 mm is quite large, especially the part below 0.075 mm. In the measured value, the specific surface area of the aggregate below 0.075 mm accounts for more than 90% of the total specific surface area of the aggregate. This is because the aggregate composition below 0.3 mm is mainly composed of mineral powder, and the recommended value in the specification is assumed to be 0.03 mm as the minimum particle size when calculating, but more than 60% of the particles with a particle size less than 0.03 mm are added to the actual mixture, so the calculated value is less than the actual value.

Therefore, this paper adopts the calculation method of specific surface area modified by actual measurement to calculate the exposed area of aggregate[24], and the calculation method is shown in Equation (2). It should be pointed out that the revised surface area coefficient is no longer based on the amount of aggregate passed through the sieve, but is replaced by the aggregate fraction of the sieve residue to ensure the accuracy of the calculation method.

$$SA = \sum (P_i \times FA_i), \quad (2)$$

where, SA is the specific surface area of aggregate; P_i is the graded sieve residue of each sieve hole; FA_i is the surface area coefficient of aggregates of different particle sizes, the value range is shown in Table 4.

Therefore, the specific surface area of aggregate can be calculated for the three gradations adopted in this study using the above calculation methods, and the calculation results are shown in Table 5. As can be seen from the calculation results in Table 5, the aggregate specific surface sum under AC-13 mix ratio is 8.778 m^2/kg, the aggregate specific surface sum under AC-16 mix ratio is 7.222 m^2/kg, and the aggregate specific surface sum under AC-20 mix ratio is 6.572 m^2/kg. Therefore, the specific surface area size order of the same weight aggregate under the three gradations is: AC-1>AC-16>AC-20.

2.3.3 Fume enrichment and measurement steps

For the designed fume generation-enrichment device, the following test steps are finally determined through testing and research:

a. According to the grading design above, weigh the aggregate and asphalt required for the test, and the total amount of asphalt mixture for each test is 1.2 kg; After weighing, the aggregate is placed in the oven at 180 ℃ to dry moisture and keep warm, and the asphalt is heated and kept warm in the oven at 145 ℃.

b. Start the heating device of the mixer, stop heating and keep warm when the temperature rises to the mixing temperature.

c. The enrichment filter tube and evaporation dish are placed in the oven and heated at 60 ℃ for 30 min to ensure that the water in the filter tube is removed clean; After drying, use a high-precision analytical balance to weigh the mass of the filter tube, recorded as m_1; Weigh the mass of the evaporating dish, denoted as M_1.

d. Pour 30 ml of weighed benzene solution into the absorption bottle, assemble the test device according to the structure shown in Figure 2 (b), and check the air tightness of the device.

e. The aggregate and asphalt, which are weighed and heated to the test temperature in advance, are poured into the mixer to start mixing, and the vacuum pump is opened to enrich the fume. The initial mixing time was 60 s. After the initial mixing was completed, the test amount of mineral powder was quickly added, the mixing pot was closed and the mixing started, so as to ensure the consistency of the test and reduce the temperature loss. The mixing time was set to 30 s. After remixing, keep the vacuum pump working for 60 s to ensure that the residual asphalt fumes in the mixing pot are pumped out. In this test, the capacity of the mixing machine was 20 L, and the pumping speed of the negative pressure vacuum pump was 0.5 L/s, so it took at least 40 s to exhaust all the residual asphalt smoke in the mixing pot after the mixing was stopped. Considering the existence of operational errors and instrument errors during the test, the continuous working time of the vacuum pump after the mixing was completed was uniformly set to 60 s.

f. After gas enrichment is completed, the filter tube is taken out of the glass test tube and put into the dust-free drying box, and dried in the oven at 60 ℃ for 30 min to remove water, and then weighed again after enrichment, the quality of the filter tube is recorded as m_2; The absorption solution in the absorption bottle is poured into the evaporating dish, and the evaporating dish is dried in the oven at 80 ℃. The mass of the evaporating dish after drying is weighed again and recorded as M_2.

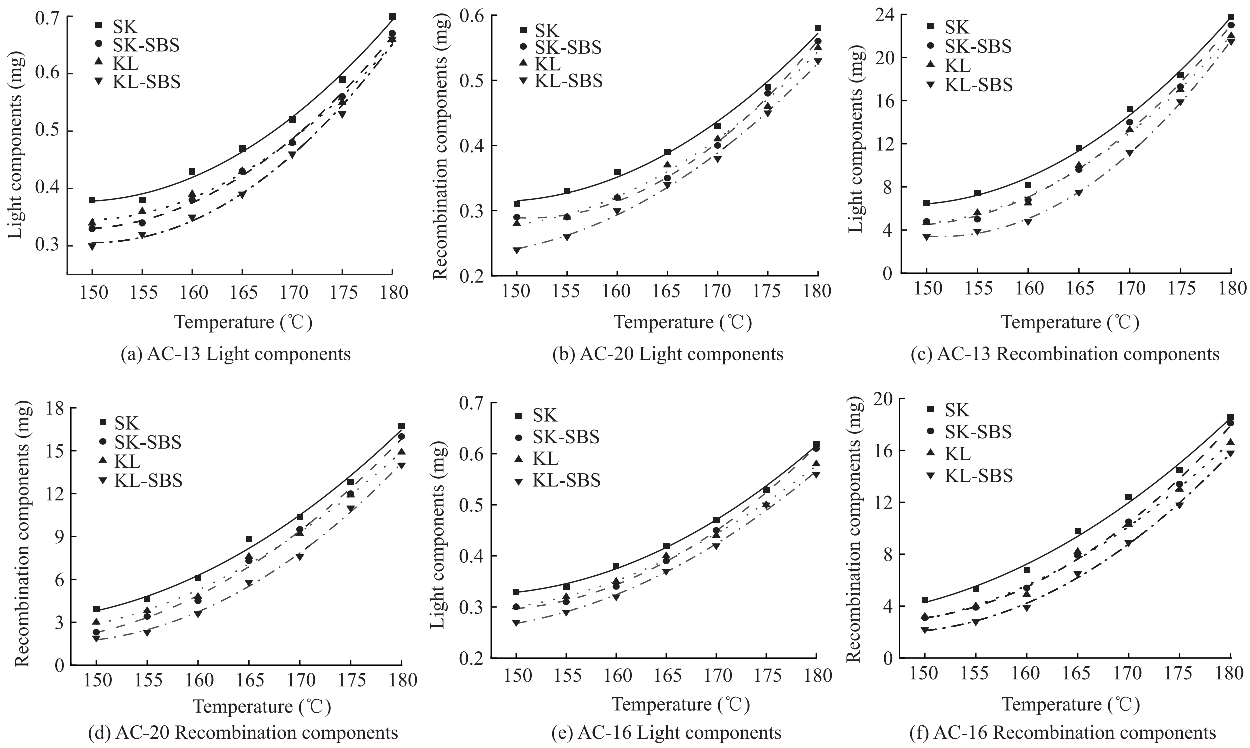
g. The fume recombination mass Q_1 and light component mass Q_2 enriched in this test are calculated by the following formula (unit mg):

$$\begin{cases} Q_1 = m_2 - m_1, \\ Q_2 = M_2 - M_1. \end{cases} \quad (3)$$

3 Analysis of influencing factors of fume release of asphalt mixture in plant

3.1 Influence of mixing temperature on fume release

In order to clarify the smoke production rule of asphalt mixture at different mixing temperatures, the smoke release results of asphalt mixture prepared by four kinds of asphalt were discussed by controlling the specific surface area of aggregate. The variation curves of light and recombination emission of fume with temperature under AC-13, AC-16 and AC-20 grades are shown in Figure 5.



(a) AC-13 Light components (b) AC-20 Light components (c) AC-13 Recombination components

(d) AC-20 Recombination components (e) AC-16 Light components (f) AC-16 Recombination components

Fig. 5 The variation of fume production of asphalt mixture with temperature

From the curve changes in Figure 5, it can be found that the emission of light and recombination components in the fume of asphalt mixture at all levels shows a similar trend with the mixing temperature, showing a non-linear increase with the increase of temperature. In addition, the temperature sensitivity of fume release is strong, and the smoke production at different temperatures shows obvious differences. This positive correlation between fume release and temperature may be due to the different temperature sensitivity of each component of asphalt. The more temperature-sensitive component will pyrolysis and release bituminous smoke at a lower temperature, and the less temperature-sensitive component will not destroy its molecular structure until it reaches its pyrolysis temperature. As the temperature rises, more and more components participate in thermal oxidation decomposition. So the more smoke is released.

Under the three gradations, the emission of light component fume is at a low level, ranging from 0.24 mg to 0.70 mg. The growth rate of light component emission increases with the increase of temperature. The growth rate reaches an extreme value when the temperature exceeds 175 ℃, and the maximum emission is reached at 180 ℃. The release amount of the recombination component ranges from 1.9 mg to 23.8 mg, and also reaches the maximum amount of fume release at 180 ℃. The magnitude difference between the lowest temperature and the highest temperature is very obvious, which further proves the strong temperature sensitivity of fume release. The emission of light fume and recombination have two jump nodes in the temperature range, which are 160 ℃ and 170 ℃ respectively. When the temperature rises from 150 ℃ to 160 ℃, the emission of light and reconstituted components of fume increases slightly and stably. When the temperature exceeds 160 ℃, the emission of light and reconstituted components of fume begins to increase, and the emission increases obviously. When the temperature reached 170 ℃, the smoke production rate of light and recombination reached the maximum, and the release of smoke almost showed a linear rapid increase in the temperature range from 170 ℃ to 180 ℃. The reason for this phenomenon may be that 160 ℃ and 170 ℃ are the key temperature nodes that cause the volatilization of asphalt components, that is, the highest pyrolysis temperature values that most of the pyrolytic components in asphalt can withstand. Therefore, when these two temperatures are reached, the smoke production rate and release amount of fume jump.

By comparing the magnitude of the release of light and recombination components in the fume, it is found that the content of recombination components in the enriched fume is much higher than that of light components, which further indicates that the fume of asphalt mixture is mainly divided into recombination groups with particle size greater than 2 μm, and the particle size of light component fume is smaller and the content is extremely low. At the same time, it was found that the fume release of KL asphalt mixture was less than that of SK asphalt at all test temperatures, which indicated that the type of asphalt would also affect the smoke production of asphalt mixture to some extent.

It is worth pointing out that compared with the base asphalt, the fume release of the asphalt mixture prepared by SBS modified asphalt is reduced, which indicates that the modifier has a certain inhibitory effect on the generation of asphalt fume. This is basically consistent with the research results of XU[23]. The adsorption of SBS modifier on the base asphalt components enhances the structural stability of molecular bonds, thus improving the thermal stability of asphalt materials. At the same time, SBS molecules also share the heat of the pyrolysis zone, resulting in a decrease in the temperature of the asphalt matrix, thus delaying the temperature rise of the asphalt components and the starting time of thermal oxidation decomposition, thus reducing the amount of fume release. It is also worth pointing out that with the increase of temperature, the inhibitory effect of SBS modifier on asphalt fume is gradually weakened. The reason may be that the structure of SBS modifier is destroyed at high temperature, resulting in the gradual failure of its binding effect on asphalt groups, and the asphalt components reach the temperature limit of pyrolysis, and the molecular bonds lose constraint and begin to break in large numbers and release smoke.

3.2 Influence of aggregate specific surface area on fume release

In order to investigate the influence of aggregate specific surface area on the fume release of asphalt mixture, the change trend of fume release of asphalt mixture the increase of temperature, the inhibitory effect of the prepared by SK and KL at the same temperature was studied. The variation trend of light fume and recombination fraction release with aggregate specific surface area is shown in Figure 6.

It can be seen from Figure 6 that under the same asphalt type and mixing temperature, the emission of light smoke and recombination components is proportional to the specific surface area of aggregate. The size of aggregate specific surface area reflects the size of asphalt exposed area, the greater the specific surface area of aggregate under the same weight, the greater the exposed area of asphalt, the greater the smoke production of asphalt mixture.

According to statistics, under the same asphalt type and mixing temperature, the smoke production of AC-16 mixture is reduced by about 20% compared with AC-13, and AC-20 is reduced by about 5% compared with AC-16. The decrease of asphalt smoke production area makes the same amount of asphalt concentrated in a smaller area, the increase of asphalt film thickness makes the fume escape channel longer, and the free organic hydrocarbons generated by the thermal oxidation decomposition of asphalt components are difficult to break away from the asphalt surface and release, which ultimately leads to the reduction of fume release.

In order to verify the applicability of the above test conclusions for different types of asphalt, the smoke light and recombination release amounts of the asphalt mixture prepared by four kinds of asphalt under different aggregate specific surface areas were discussed at the mixing temperatures of 150 ℃ and 180 ℃. The test results are shown in Figure 7.

The data in Figure 7 more directly verified the above conclusions: for different asphalt types, the emission amounts of light smoke and recombination components are positively correlated with the specific surface area size of aggregate, and the differences between the emission amounts of AC-16 and AC-13 grades are more obvious than those of AC-20 grades. In addition, the fume emission of the asphalt mixture prepared by SK asphalt is greater than that of KL asphalt under all the gradations. SBS modifier can inhibit the production of fume, but with inhibitor on fume is gradually weakened.

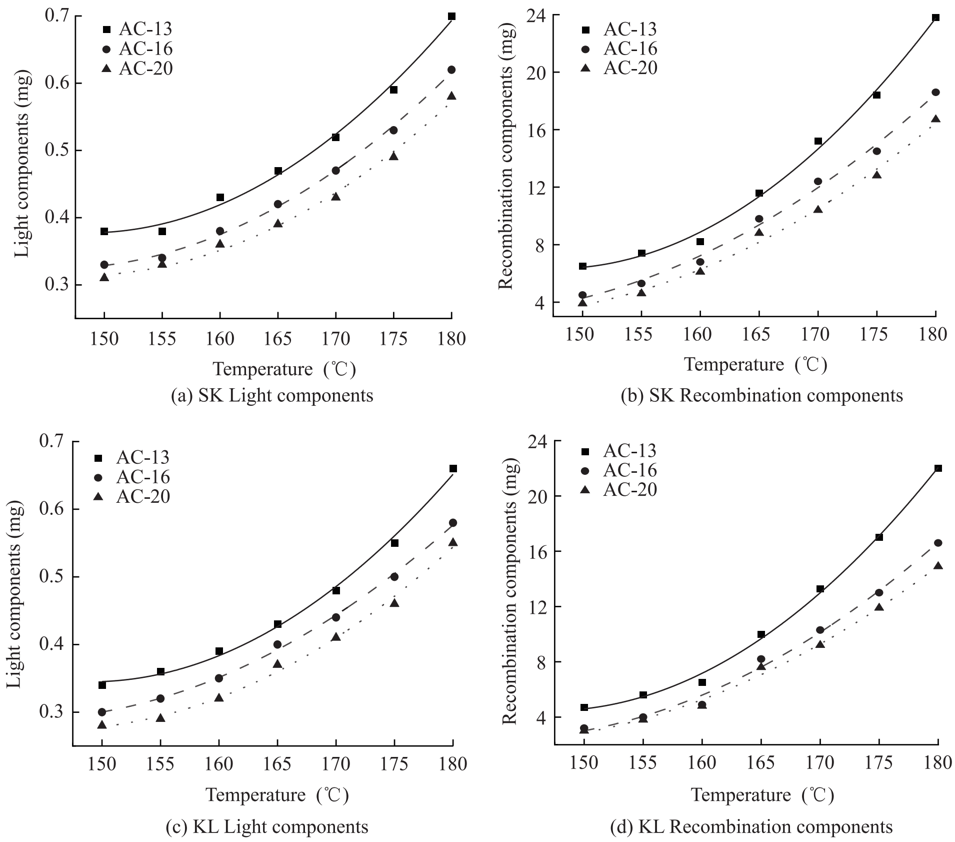


Fig. 6 Variation of fume production of asphalt mixture with gradation

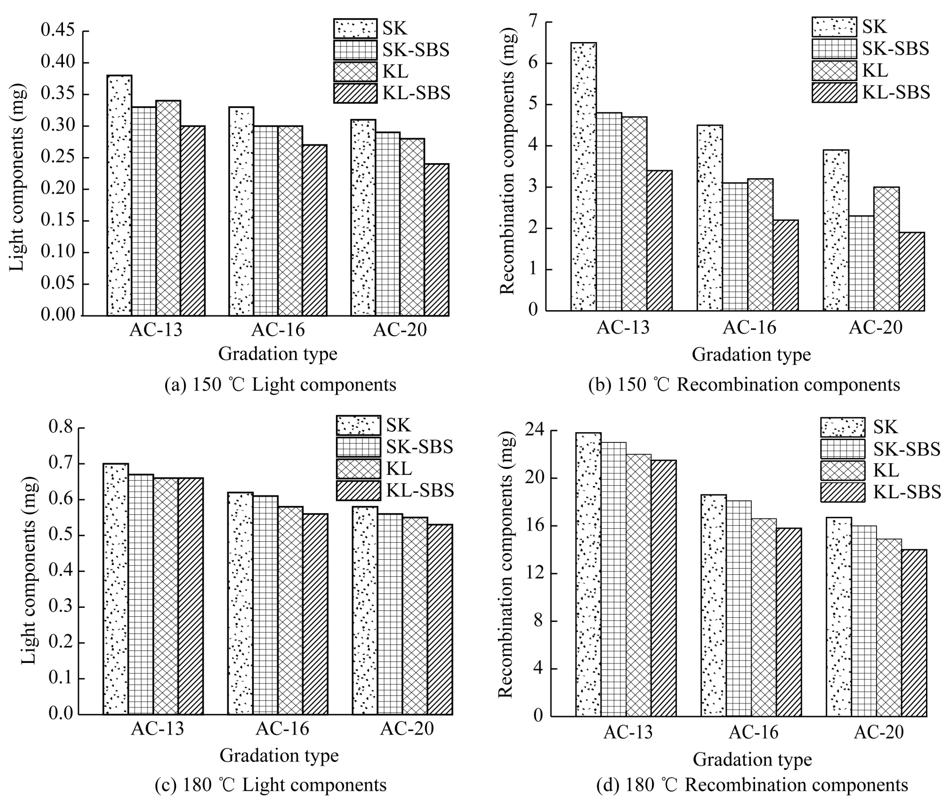


Fig. 7 Variation of fume production of asphalt mixture with gradation

3.3 Effect of mixing frequency on fume release

In order to investigate the influence of different mixing frequency on the smoke release of asphalt mixture, the smoke production trend of AC-13 grade mixture prepared by SK and KL was studied at the same temperature with mixing frequency. The variation of light fume and recombination component release with mixing frequency is shown in Figure 8.

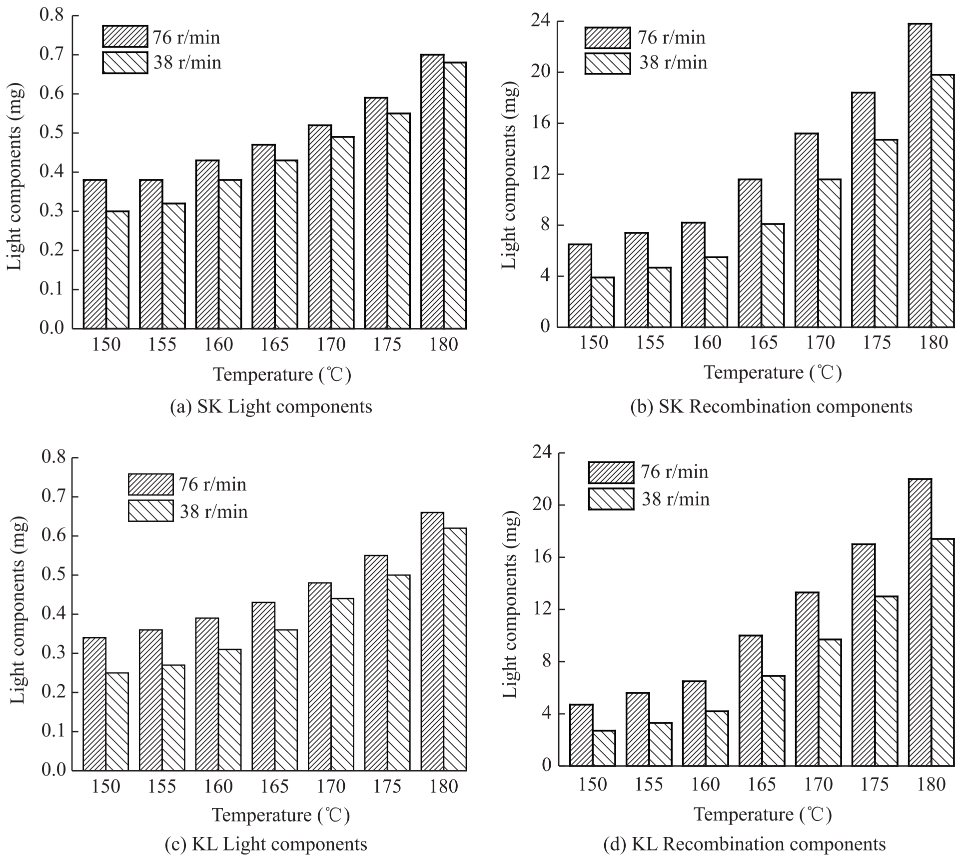


Fig. 8 Variation of fume production of KL asphalt mixture with mixing frequency

It can be seen from the data in Figure 8 that, at each temperature node, the fume release amount of asphalt mixture at low frequency mixing decreases compared with that at high frequency mixing, and the effect of mixing rate on the release amount of light components is less than that of recombination fraction. This may be due to the fact that with the increase of mixing frequency, the asphalt attached to the aggregate surface will have more frequent contact with the air, and the stirring action accelerates the air flow in the mixing space, which makes the thermal oxidation reaction of the asphalt components more adequate, so the release of fume is correspondingly larger. In addition, the group responsible for generating light component fume in asphalt is less dependent on oxygen concentration, and the particles of light component fume are small, and its escape diffusion is not affected by the aggregate accumulation time, so the release amount of light component is relatively small affected by the mixing rate.

It is worth pointing out that with the increase of temperature, the influence weight of mixing frequency on the fume release of asphalt mixture gradually decreases. Taking SK asphalt as an example, the recombination fraction release of low-frequency mixing at 150 ℃ is about 60% of that of high-frequency mixing, and that of low-frequency mixing at 180 ℃ is about 83% of that of high-frequency mixing. It can be concluded that mixing temperature is the most important factor affecting the fume release of asphalt mixture. In addition, it can be observed that under the same mixing frequency, the fume emission increases with the increase of temperature, which is consistent with the above conclusion.

Table 3 Aggregate surface area coefficient of each particle size

Sieve size (mm)	≥4.75	2.36	1.18	0.6	0.3	0.15	0.075
Surface area coefficient FA_i	0.41	0.82	1.64	2.87	6.14	12.29	32.77

Table 4 Aggregate surface area coefficient of each particle size

Sieve size (mm)	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	0
Surface area coefficient FA_i	0.08	0.09	0.11	0.15	0.27	0.46	0.96	1.71	3.48	5.25	10.72	113.77

Table 5 Calculation of specific surface area of aggregate

Sieve size (mm)		19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	0
Surface area coefficient FA_i		0.08	0.09	0.11	0.15	0.27	0.46	0.96	1.71	3.48	5.25	10.72	113.77
Scoring sieve residue (%)	AC-13	0	0	6.4	20.8	18.4	17.2	9.5	9.63	4.69	4.58	2	6.8
	AC-16	0	6.5	9.7	17.3	18.6	16.6	7.9	6.4	4.2	4.1	3	5.7
	AC-20	4	11	11.5	10.5	21	13	9	7	3.5	2.5	2	5
Specific surface area (m^2/kg)	AC-13	0	0	0.70	3.12	4.97	7.91	9.12	16.47	16.32	24.05	21.44	773.66
	AC-16	0	0.59	1.07	2.6	5.02	7.64	7.58	10.94	14.62	21.53	32.16	648.49
	AC-20	0.32	0.99	1.27	1.58	5.98	5.52	8.64	11.97	12.18	13.13	26.80	568.85

4 Conclusions

(1) A set of fume generation and enrichment device which can simulate the mixing state of asphalt mixing plant is proposed, and its reliability is verified. Effective enrichment of asphalt fume by means of physical (filter) and chemical (benzene absorber) enrichment can improve the accuracy of experimental data.

(2) The magnitude of light and reconstituted components in the fume varies greatly under different mixing conditions. The filter membrane with a pore size of 2 μm can enrich most of the asphalt fume, and the asphalt fume is mainly composed of reconstituted components.

(3) The fume release of asphalt mixture is affected by the type of asphalt. Under different mixing conditions, the fume release of SK asphalt mixture is greater than that of KL asphalt mixture. SBS modifier has a certain inhibition effect on the release of smoke. SBS modifier enhances the molecular structural stability by adsorption of asphalt components, and then enhances the thermal stability of asphalt smoke producing part.

(4) Mixing temperature is the most important factor affecting the emission of fume, the emission of fume increases with the increase of mixing temperature, and the chemical components in asphalt will be pyrolyzed and released at a specific temperature, and the less sensitive components will pyrolyze earlier, and vice versa.

(5) The fume release is negatively correlated with the specific surface area of aggregate. The larger the aggregate gradation, the smaller the fume release. The specific surface area of aggregate directly affects the fume release amount by determining the exposed area of asphalt.

(6) The fume release is positively correlated with the mixing frequency. The faster the mixing frequency, the longer the contact time between asphalt and air, the fuller the thermal oxidation reaction in the fume producing part of asphalt, and the greater the fume production volume. Meanwhile, it is found that the influence of mixing frequency on the output of light components is significantly reduced compared with the recombination fraction.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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