

Article

Emission Risk and Inhibition Technology of Asphalt Fume from Crumb Rubber Modified Asphalt

Zipeng Wang ^{1,2,3,*}, Hui Li ¹ , Ming Jia ^{1,4} and Qunle Du ²

¹ Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai 201804, China; hli@tongji.edu.cn (H.L.); jiamingtj@tongji.edu.cn (M.J.)

² Hebei Transportation Investment Group Company Limited, Shijiazhuang 050019, China

³ Hebei Tonghua Highway Materials Co., Ltd., Shijiazhuang 050019, China

⁴ Urban Mobility Institute, College of Transportation Engineering, Tongji University, Shanghai 201804, China

* Correspondence: 2080078@tongji.edu.cn

Abstract: Crumb rubber-modified asphalt mixtures have been proven to have extensive utilization value in road engineering. However, the rubber releases more fumes during the construction period, which causes severe harm to human health and the environment. This research focused on the emission risk of asphalt fume from crumb rubber-modified asphalt, and then the inhibition technology was also optimized. Firstly, the emission behavior and the hazardous evaluation of the asphalt fume from crumb rubber-modified asphalt were investigated. Then, the characteristics of the inhibition materials were evaluated. Finally, the reduction in the emission of inhibited crumb rubber-modified asphalt fume was identified, and the optimized formula was determined based on the inhibition effect, rheological properties, and cost. The results indicate that crumb rubber-modified asphalts release more fume components with an increment in the temperature and crumb rubber content. Desulfurized rubber reduces the release of H₂S and NO. Benzene compounds, including paraxylene, toluene, and benzene, are the most released pollutants that harm human health, especially DS CRA 20% and CRA 50%. Kaolin powder and expanded graphite have a sufficient pore structure and volume, the addition of which reduces the release of pollutants while possibly promoting the release of NO and H₂S. Their addition also has a significant control effect on the release of particulate matter at 170 °C and 185 °C. With the consideration of emissions, rheological properties, and cost, CRA 40%-EG2%-KL2% was determined as the optimization formula. This research is helpful to the application of crumb rubber-modified asphalt in road construction and maintenance.

Keywords: crumb rubber; asphalt fume; VOCs; inhibition



Citation: Wang, Z.; Li, H.; Jia, M.; Du, Q. Emission Risk and Inhibition Technology of Asphalt Fume from Crumb Rubber Modified Asphalt. *Sustainability* **2024**, *16*, 8840. <https://doi.org/10.3390/su16208840>

Academic Editor: Edoardo Bocci

Received: 30 August 2024

Revised: 24 September 2024

Accepted: 3 October 2024

Published: 12 October 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the rapid development of the transportation industry and more crowded traffic flow, asphalt pavements are damaged prematurely during the service period, shortening their service life [1,2]. A method to improve the road performance of asphalt mixtures and extend service life has become a research focus [3,4]. At present, SBS-modified asphalt and rubber-modified asphalt are widely used. Compared with SBS-modified asphalt, rubber-modified asphalt has been selected by engineers and construction companies due to its lower cost and excellent road performance [5,6]. It is widely used in the pavements of highways, with modified asphalt with a 30% rubber content or less as the typical ratio [7]. In order to maximize the benefits of road construction and increase the recycling of waste tires, researchers are working hard to achieve the engineering application of high-content rubber-modified asphalt [8,9]. However, the production and use of high-content rubber-modified asphalt also introduce pungent odors, such as H₂S, and toxic and harmful gases, such as benzothiazole [10]. In addition, environmental impacts such as increased asphalt fume emissions cannot be ignored [11,12].

Volatile organic compounds (VOCs) are referred to as organic compounds that are easily volatilized within a certain temperature range [13,14]. The organic hydrocarbon compounds in asphalt volatilize during their utilization [15,16]. Relevant studies by environmental departments in the United States, the European Union, Canada, Australia, and other countries have shown that the air pollution hazards of asphalt materials need to be further paid attention to, and corresponding emission standards have been formulated [17,18]. A series of studies have been conducted on the release law of asphalt fumes, confirming the harm of asphalt fumes to the human body and the pollution of the environment, especially the impact of asphalt fumes on the health of construction workers and surrounding residents [19]. In comparison with traditional asphalt, the emission of rubber-modified asphalt is markedly elevated, which significantly constrains the extensive utilization of rubber-modified asphalt and its potential applications [20,21]. This phenomenon can be attributed to two principal factors. The viscosity of rubber-modified asphalt is high, necessitating a high construction temperature, which, in turn, gives rise to a considerable increase in volatile organic compounds in asphalt [22,23]. Additionally, the high concentration of sulfur compounds present in rubber powder results in their volatilization and subsequent release during the construction process, further exacerbating the emission pollution issue associated with the utilization of rubber-modified asphalt [24–26]. The large-scale application of rubber-modified asphalt and the increasing demand for the clean paving of asphalt pavement in the highway engineering industry have led to a greater focus on the composition, escape behavior, and inhibition technology of harmful volatiles in rubber-modified asphalt [27,28]. This has significant potential for providing effective environmental data support and environmentally friendly adaptability for rubber-modified asphalt [29,30].

A lot of research has been conducted on the release behavior, evaluation methods, and inhibition technology of asphalt fume, especially on methods to reduce the emission of asphalt fume [31,32]. By adding foaming agents, viscosity reducers, surfactants, etc., to reduce the mixing temperature, VOC emissions can be effectively reduced [33,34]. Studies have shown that at different temperatures (100 °C, 130 °C, 160 °C, 190 °C, and 220 °C), the inhibition efficiency of calcium hydroxide zeolite for asphalt VOCs is 26.6%, 33.4%, 35.0%, 30.5%, and 24.9%, respectively [35]. The introduction of catalytic active agents, such as tourmaline and nano-titanium dioxide, has shown that adding 3% nano-titanium dioxide (TiO₂) to asphalt can reduce the release of asphalt fumes by 30%, adding 0.5% graphite-phase carbon nitride (g-C₃N₄) can inhibit the release of asphalt fume by 50%, and adding a 17–20% graphene–tourmaline mixed powder can reduce the release of asphalt fume by 76.9–80.5% [36,37]. Some researchers have also tried to add porous activated carbon to asphalt materials [38]. Adding such substances can adsorb light components in asphalt, increase the viscosity of asphalt, absorb light components during the heating of asphalt to reduce the release of asphalt fume, and adsorb volatiles [39]. Studies have shown that compared with PJ90 matrix asphalt, 3%, 4%, and 5% activated carbon can reduce VOCs' release by 26.9%, 30.7%, and 32.6%, respectively [40]. These methods include high costs, the restricted efficacy of smoke suppression, and the potential reduction in the performance of the asphalt mixtures [37,41]. The objective of researchers is to identify smoke-suppression technology that is cost-effective, highly efficient, and does not compromise the performance of the mixture [42].

The preceding analysis demonstrates that the analysis of the asphalt fume composition has played a pivotal role in curbing the environmental impact of pavement paving through the implementation of effective suppression measures [43]. However, research into the fume of crumb rubber-modified asphalt remains relatively limited. This study aims to address this gap in knowledge by investigating the use of inhibition materials in rubber powder-modified asphalt. This study focuses on the emission risk of asphalt fumes from crumb rubber-modified asphalt and the proposed inhibition technology. Firstly, the release behavior was studied, the pollutants were identified, and the hazardous evaluation of asphalt fume from crumb rubber-modified asphalt was performed. Then, the surface in micro-scale

and pores characteristics of inhibition materials were evaluated. Finally, a reduction in the emission of inhibited crumb rubber-modified asphalt was identified, and the optimization formula was determined based on inhibition, rheological properties, and cost.

2. Materials and Methods

2.1. Raw Materials

Crumb rubber-modified asphalt used in this study was selected as 20% crumb rubber-modified asphalt (CRA 20%), 20% desulfurized crumb rubber-modified asphalt (DS CRA 20%), 30% crumb rubber-modified asphalt (CRA 30%), 40% crumb rubber-modified asphalt (CRA 40%), and 50% crumb rubber-modified asphalt (CRA 50%), which are produced by Hebei Jiaotou Special Material Technology Co., Ltd, Hebei, China. Indicators of representative product are shown in Table 1. The preparation of crumb rubber-modified asphalt adopts microwave radiation low-temperature and high-efficiency desulfurization technology.

Table 1. Basic performance parameters of 40% crumb rubber-modified asphalt.

Indicators	Unit	Value	Test Method [44]
Kinematic viscosity (180 °C)	Pa•S	2.85	T0625-2011
Penetration (25 °C, 100 g, 5 s)	0.1 mm	43	T0604-2011
Ductility (5 cm/min, 15 °C)	cm	18.6	T0605-2011
Softening point	°C	78.9	T0606-2011
Separation difference in softening point	°C	2.4	T0661-2011
Residue after RTFOT	Mass change	%	−0.2
(163 °C, 85 min)	Penetration ratio	%	87
	Ductility (5 °C)	cm	14.5

Expanded graphite and kaolin powders have sufficient pore structures and large specific surface areas, showing the potential fume-adsorption capacity to reduce emission, which is selected as inhibition materials in this research. Figure 1 shows the appearance of kaolin powders and expanded graphite powders.

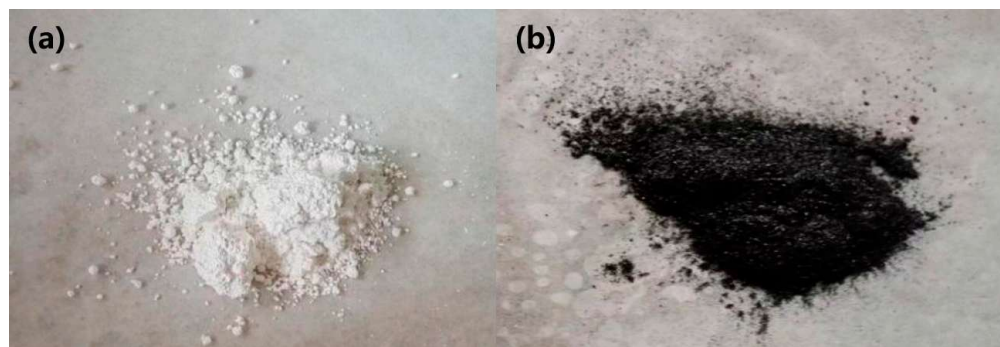


Figure 1. Appearance of inhibition materials: (a) Kaolin and (b) Expanded graphite.

2.2. Preparation of Inhibited Crumb Rubber-Modified Asphalt

CRA 40% was selected as the matrix; meanwhile, kaolin powders and expanded graphite were used to prepare inhibited crumb rubber-modified asphalt. The preparation schemes are shown in Table 2, and the preparation process and preparation parameters are shown in Table 3.

Table 2. Preparation scheme.

Sample	Addition Amount (by Weight of Asphalt)	
	EG	KL
CRA 40%-KL6%	0%	6%
CRA 40%-EG6%	6%	0%
CRA 40%-EG3%-KL3%	3%	3%
CRA 40%-EG2%-KL2%	2%	2%
CRA 40%-EG1%-KL1%	1%	1%

Table 3. Preparation process and parameters.

Parameters	Process		
	I. Heating and Stirring	II. High-Speed Shearing	III. Dissolving and Stirring
Temperature (°C)	180	180	180
Rate RMP)	400	3–4 k	400
Time (min)	30	60	30

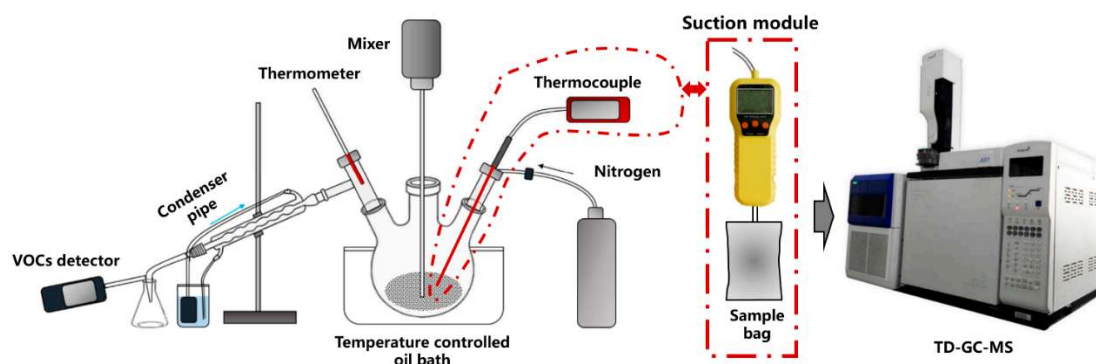
2.3. Experimental Methods

2.3.1. Inhibition Material Characteristics

The characterization of surface appearance of inhibition materials was conducted by a Quanta FEG 450 scanning electron microscope (SEM) manufactured by FEI, Hillsboro, OR, USA. The pore distributions and surface areas of inhibition material were tested using an ASAP 2460 apparatus produced by Micromeritics, Norcross, GA, USA; the adsorbate was nitrogen (N₂).

2.3.2. Detection and Analysis System of Asphalt Fumes

Figure 2 shows a set of collection and evaluation devices for asphalt fumes developed in our previous study [45]. In this research, 120 °C, 170 °C, and 185 °C were selected to control fume production. A composite gas component analyzer was used to directly analyze VOCs, SO₂, H₂S, NO, and PM pollutants in asphalt fumes. Thermal desorption–gas chromatography–mass spectrometry (TD-GC-MS) was used to analyze specific types and relative proportions of organic volatiles from asphalt fumes. The sample for the TD-GC-MS evaluation was obtained from thermal desorption tube, where the asphalt fumes from the three-necked flask at the rate of 500 mL/min for 2 min were fixed.

**Figure 2.** Detection and analysis system of asphalt fumes.

2.3.3. Rheological Test

The rheological properties of inhibited crumb rubber-modified asphalt were tested using a dynamic shear rheometer for further selection of the inhibitor formula. Temperature sweep was conducted with the test temperature of 58 °C, 64 °C, 70 °C, 76 °C, and 82 °C.

The heating rate was 2 °C/min, the strain control was 0.1%, and 25 mm and 1 mm were determined as the plate diameter and the plate gap, respectively.

2.4. The Basic Experiment Line

The basic experimental process is shown in Figure 3.

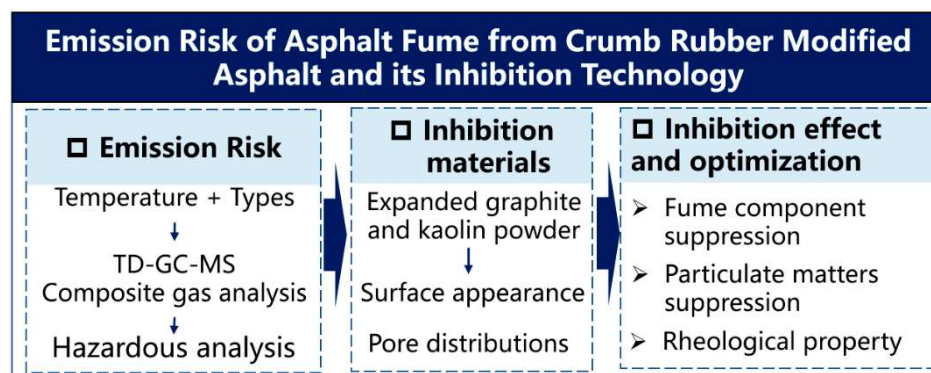


Figure 3. The basic experiment process used in the research.

3. Results and Discussions

3.1. Emission Risk of Crumb Rubber-Modified Asphalt

The released result of VOCs from crumb rubber-modified asphalt at different temperatures is shown in Figure 4a. It was found that crumb rubber-modified asphalt released more fume at high temperatures, but the VOC concentration released by CRA 20%, CRA 40%, and CRA 50% at 185 °C was lower than that at 175 °C, which was caused by the VOCs in the asphalt fume being released during the heating process, so there is a partial decrease at 185 °C. The result also indicates that more added rubber powder results in more released VOCs at 170 °C: the VOC concentration released by CRA 50% at 170 °C reached 221 ppm; the VOC concentration of DS CRA 20% was almost twice that of CRA 20%, and the release is the highest at 120 °C, reaching 71 ppm. This also shows that the addition of materials during the disposal of desulfurized rubber powder produces additional VOCs under lower temperature conditions. The NO release result at different temperatures is shown in Figure 4b. DS CRA 20% would not release NO under the conditions, while CRA 20% released the highest NO concentration at 185 °C, reaching 12 ppm, and only 2.9 ppm at 170 °C. CRA 40% released the highest NO at 170 °C, reaching 6.3 ppm, and less NO was released by CRA 50% and CRA 30%. The SO₂ release result at different temperatures is shown in Figure 4c. Only 50% of CRA released SO₂ at 170 °C and 185 °C, respectively, and SO₂ was not detected in other crumb rubber-modified asphalt samples. The H₂S release result at different temperatures is shown in Figure 4d. The release of DS CRA 20% is much lower than that of other crumb rubber-modified asphalts, and the release at 185 °C was only 1.2 ppm. The desulfurization process has an obvious inhibitory effect on the release of H₂S.

The release of particulate matter at different temperatures is shown in Figure 5. PM 1.0 release at 120 °C is significantly lower than that of 170 °C and 185 °C. The concentration of CRA 40% at 170 °C is the highest, reaching 700 ug/m³, which is 6–7 times compared to the release of other samples under the same temperature conditions. The particulate matter release of CRA 20%, CRA 30%, and CRA 50% increases with the increment of temperature. However, the release of DS CRA 20% and CRA 40% at 180 °C is lower than that at 170 °C. In the PM 1.0 results, CRA 40% has the largest release at 170 °C, reaching 700 ug/m³. At 120 °C, CRA 30% has the largest release, which is 66 ug/m³. In the PM 2.5 results, the crumb rubber-modified asphalt releases similar amounts, and the release at 185 °C is slightly less than that at 170 °C. CRA 40% releases the most at 170 °C, reaching 1300 ug/m³. At 120 °C, CRA 30% releases the most, at 106 ug/m³. In the PM 10.0 results, CRA 50% releases the most at 170 °C, reaching 2591 ug/m³. At 120 °C, CRA 30% releases the most, at 126 ug/m³.

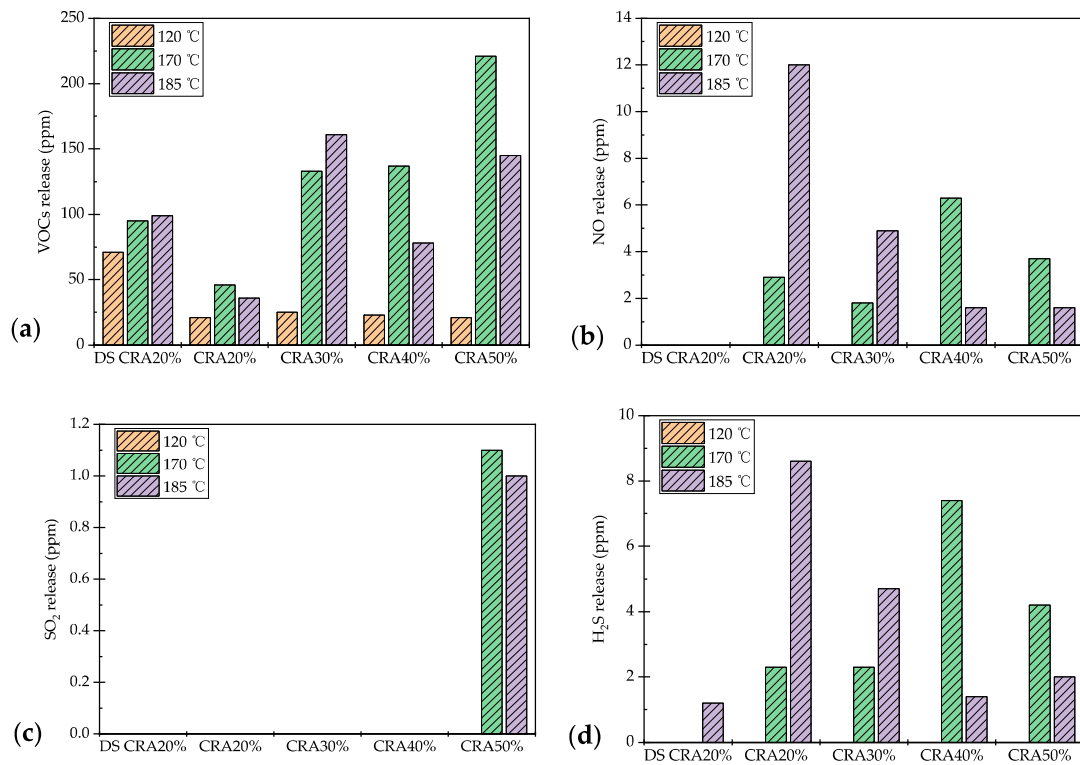


Figure 4. Release of gas from crumb rubber-modified asphalt at different temperatures: (a) VOCs, (b) NO, (c) SO₂, and (d) H₂S.

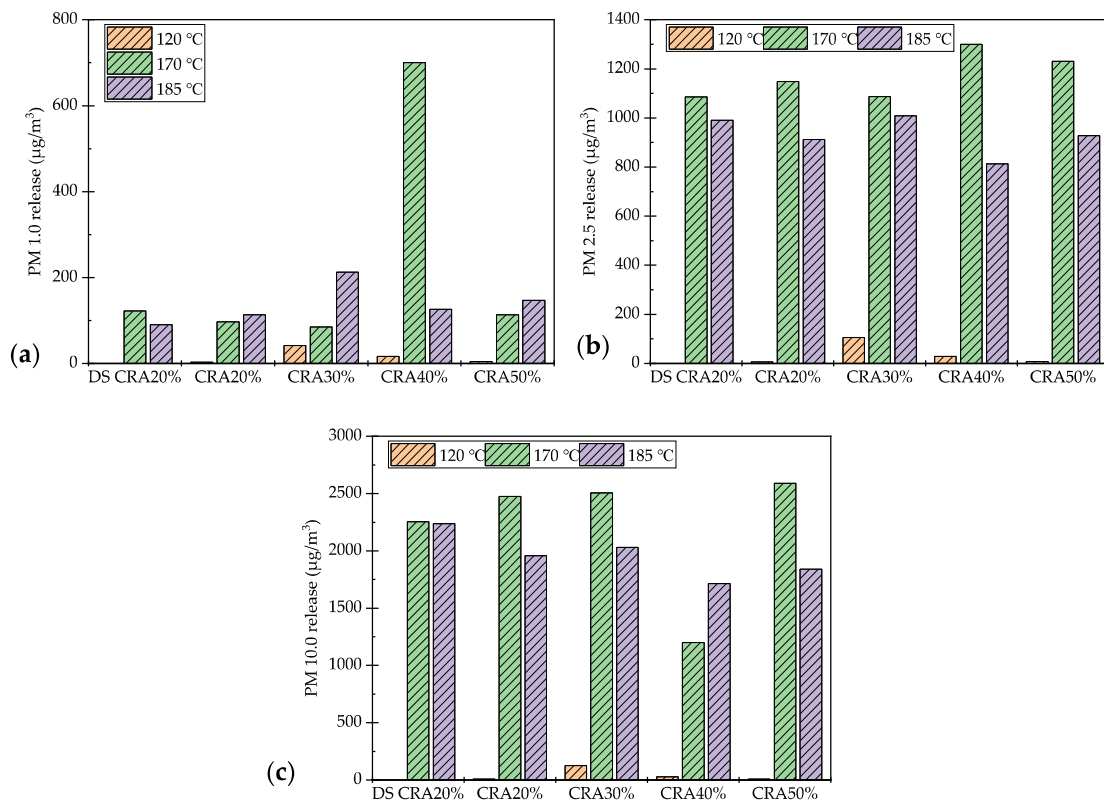


Figure 5. Releases of particulate matter from crumb rubber-modified asphalt at different temperatures: (a) PM 1.0, (b) PM 2.5, and (c) PM 10.0.

Figure 6a illustrates the top 20 pollutants released from CRA 20% at 120 °C, 170 °C, and 185 °C. The peak area comparison indicates that most pollutants exhibited a higher released rate at elevated temperatures, with a relatively slight difference between 170 °C and 185 °C. It can be observed that acetic acid, ethylenecyclobutane, p-ethylenediamine, undecane, and propionic acid were predominantly released at 185 °C, which were hard to detect in the other temperatures. This was caused by the different saturated vapor pressures of various substances, which resulted in the production of volatiles at varying temperature stages. The results of DS CRA 20% are illustrated in Figure 6b. As with CRA 20%, most pollutants were released at high temperatures. However, the addition of a desulphurization process to reduce the release of pollutants, such as hydrogen sulfide, results in the production of many other pollutants, including benzothiazole and naphthalene. These pollutants are more toxic and potentially carcinogenic. Therefore, further optimization of desulphurization processes was needed urgently. The results of CRA 30%, CRA 40%, and CRA 50% are shown in Figure 6c, d and e, respectively. As with CRA 20%, most pollutants were released at elevated temperatures. However, compared to the components released by CRA 20% and CRA 30%, additional benzothiazole and naphthalene of CRA 40% were produced, which may pose a carcinogenic risk. Most of the pollutants are released by CRA 50% at high temperatures. Similar to DS CRA 20% and CRA 40%, additional benzothiazoles, naphthalenes, and tetrahydrofurans are produced, with their relative amounts being significantly higher than those of CRA 40%. This indicates a higher potential carcinogenic risk compared to the released components of CRA 20% and CRA 30%.

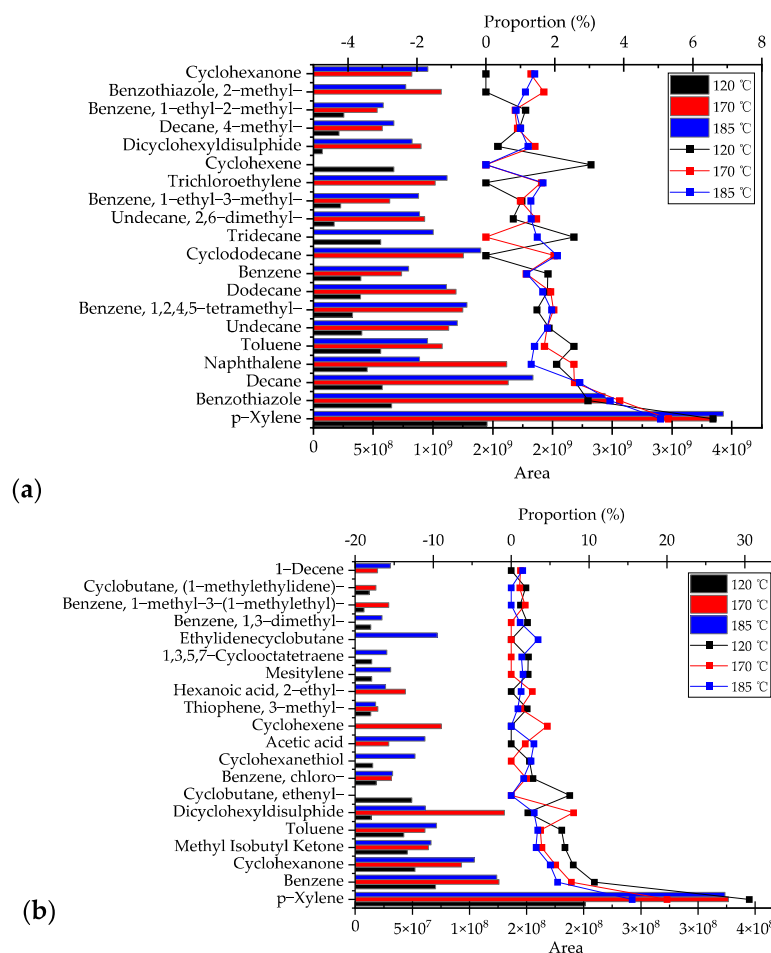


Figure 6. Cont.

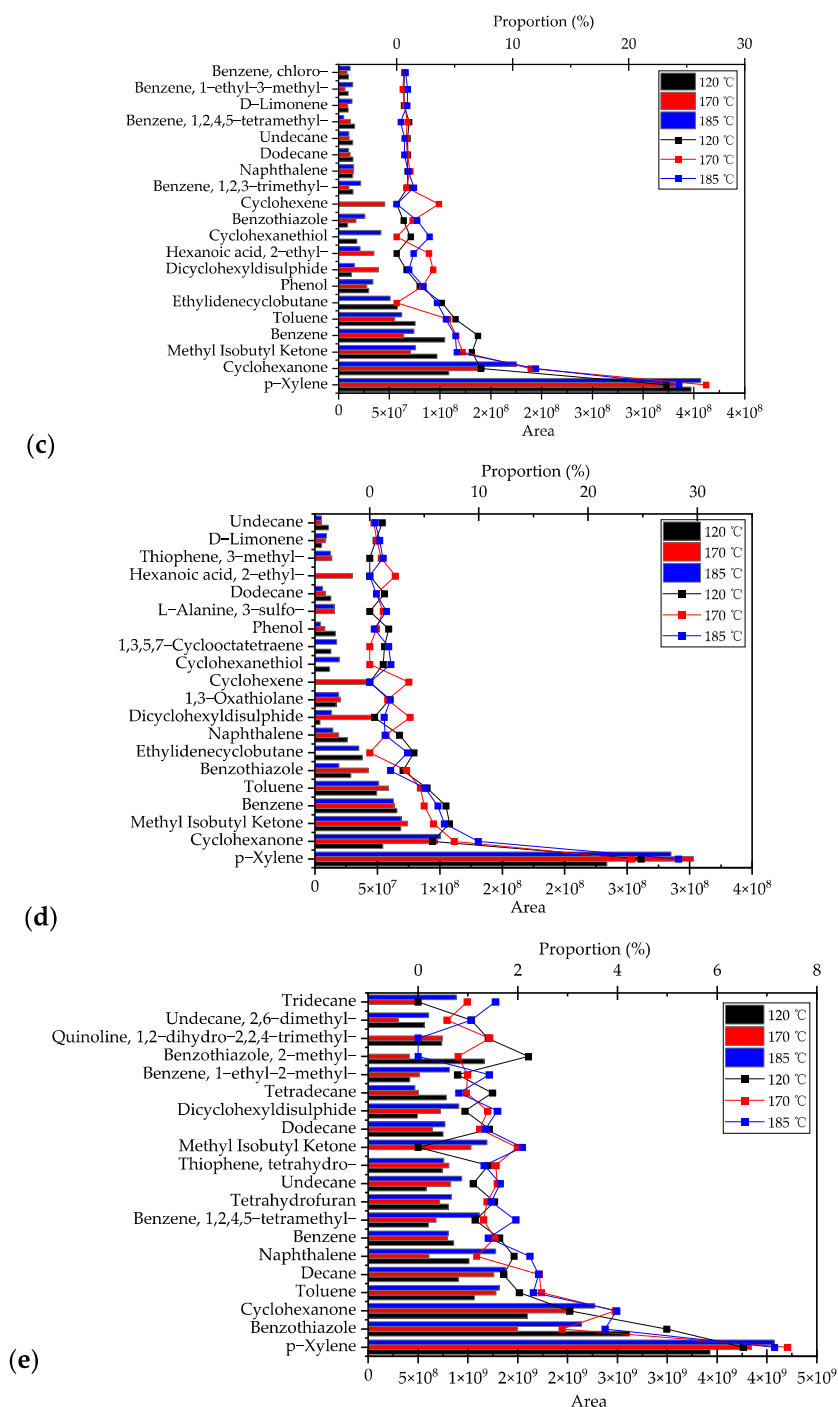


Figure 6. Proportion of top 20 pollutants released from crumb rubber-modified asphalt: (a) DS CRA 20%, (b) CRA 20%, (c) CRA 30%, (d) CRA 40%, and (e) CRA 50%.

Figure 7 shows the average top 20 pollutants released from the five types of crumb rubber-modified asphalt at 120 °C, 170 °C, and 185 °C. It can be found that the top ten substances with the largest proportions are p-xylene (17.1%), cyclohexanone (5.77%), benzene (4.57%), methyl isobutyl ketone (3.86%), toluene (3.66%), benzothiazole (2.29%), dicyclohexyl disulfide (2.03%), naphthalene (1.39%), ethylene cyclobutane (1.22%), and cyclohexene (1.15%). The fume components mainly include benzene series, polycyclic aromatic hydrocarbons, alkanes, etc. Compared with the fume composition of base asphalt that has been studied, the main components of base asphalt are linear alkanes and olefins, side chain alkanes, and olefins, as well as toluene and p-xylene, and the benzene series

accounts for only about 4~5%; the main pollutants are mainly alkanes. Therefore, the production of benzene series, sulfur-containing organic matter, ketones, and ether substances significantly increased in crumb rubber-modified asphalt.

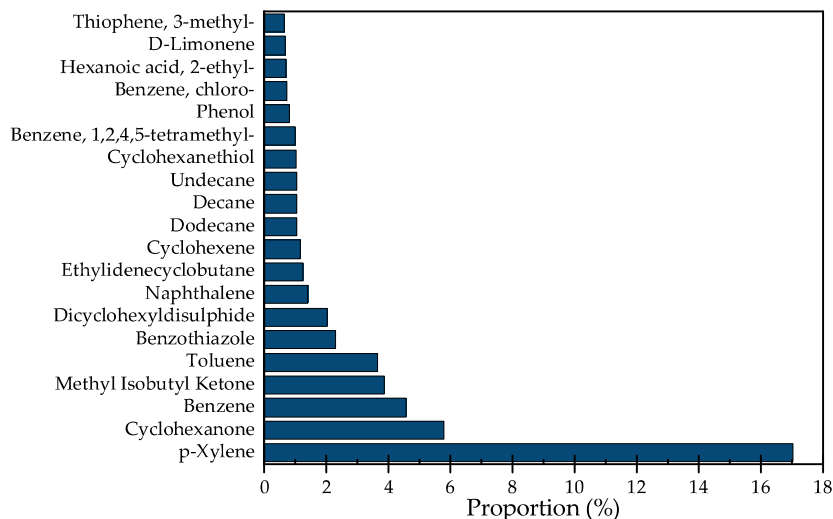


Figure 7. Top 20 pollutants (averaged) released from crumb rubber-modified asphalt.

Figure 8 shows the risk classification of pollutants from the fume of crumb rubber-modified asphalt. The risk of the substances can be divided into high risk, medium risk, low risk, and slight risk. The potential for adverse health effects is significant when individuals are exposed to high-risk substances over an extended period. These effects include cancer, as well as severe respiratory and neurological damage. Substances classified as medium risk are moderately toxic and have the potential to damage organs such as the nervous system, liver, or kidneys, as well as cause respiratory and skin irritation. Low-risk substances present a relatively low risk to humans, with significant health effects typically occurring only at high concentrations or with prolonged exposure. Slight-risk substances pose a very low hazard to humans and, under normal conditions of use or exposure, pose little or no significant health risk. It can be found in Figure 8 that Benzene, Trichloroethylene, Naphthalene, Benzothiazole, Phenol, and Benzene, chloro- were included in the high-risk category; Cyclohexanone, Methyl Isobutyl Ketone, Toluene, Thiophene, 3-methyl-, Cyclohexanethiol, 1,3,5,7-Cyclooctatetraene, Thiophene, tetrahydro-, Hexanoic acid, 2-ethyl-, Mesitylene, and Dicyclohexyldisulphide were classified as medium risk; p-Xylene, Ethylidenecyclobutane, Decane, Dodecane, Undecane, Tridecane, Cyclododecane, Decane, 4-methyl-, Benzene, 1,2,4,5-tetramethyl-, Benzene, 1,3-dimethyl-, Benzene, 1-ethyl-2-methyl-, Benzene, 1-ethyl-3-methyl-, Benzene, 1,2,3-trimethyl-, Benzothiazole, and 2-methyl- were classified as low risk; and Cyclobutane, ethenyl-, L-Alanine, 3-sulfo-, Quinoline, 1,2-dihydro-2,2,4-trimethyl-, Cyclohexene, 1-Decene, Acetic acid, 1,3-Oxathiolane, D-Limonene, and Tetrahydrofuran were included in the slight-risk category.

To quantify the effects of risky pollutants on the human body, a hazardous index was proposed as a means of measuring the potential risks associated with these substances, which was defined in Equation (1):

$$\text{Hazardous index} = \sum R_i \times W_i \quad (1)$$

where R_i is defined as the hazard rating of the substances (5: high risk, 4: medium risk, 3: low risk, 2: slight risk, 1: safe), and W_i is the intensity area shown in Figure 6.

CRA-20%	DS CRA-20%	CRA-30%	CRA-40%	CRA-50%
p-Xylene	p-Xylene	p-Xylene	p-Xylene	p-Xylene
Benzene	Benzo[thiazole]	Cyclohexanone	Cyclohexanone	Benzo[thiazole]
Cyclohexanone	Decane	Methyl Isobutyl Ketone	Methyl Isobutyl Ketone	Cyclohexanone
Methyl Isobutyl Ketone	Naphthalene	Benzene	Benzene	Toluene
Toluene	Toluene	Toluene	Toluene	Decane
Dicyclohexyldisulphide	Undecane	Ethylidenecyclobutane	Benzo[thiazole]	Naphthalene
Cyclobutane, ethenyl-	Benzene, 1,2,4,5-tetramethyl-	Phenol	Ethylidenecyclobutane	Benzene
Benzene, chloro-	Dodecane	Dicyclohexyldisulphide	Naphthalene	Benzene, 1,2,4,5-tetramethyl-
Cyclohexanethiol	Benzene	Hexanoic acid, 2-ethyl-	Dicyclohexyldisulphide	Tetrahydrofuran
Acetic acid	Cyclododecane	Cyclohexanethiol	1,3-Oxathiolane	Undecane
Cyclohexene	Tridecane	Benzo[thiazole]	Cyclohexene	Thiophene, tetrahydro-
Thiophene, 3-methyl-	Undecane, 2,6-dimethyl-	Cyclohexene	Cyclohexanethiol	Methyl Isobutyl Ketone
Hexanoic acid, 2-ethyl-	Benzene, 1-ethyl-3-methyl-	Benzene, 1,2,3-trimethyl-	1,3,5,7-Cyclooctatetraene	Dodecane
Mesitylene	Trichloroethylene	Naphthalene	Phenol	Dicyclohexyldisulphide
1,3,5,7-Cyclooctatetraene	Cyclohexene	Dodecane	L-Alanine, 3-sulfo-	Tetradecane
Ethylidenecyclobutane	Dicyclohexyldisulphide	Undecane	Dodecane	Benzene, 1-ethyl-2-methyl-
Benzene, 1,3-dimethyl-	Decane, 4-methyl-	Benzene, 1,2,4,5-tetramethyl-	Hexanoic acid, 2-ethyl-	Benzo[thiazole], 2-methyl-
Benzene, 1-methyl-3-(1-methylethyl)-	Benzene, 1-ethyl-2-methyl-	D-Limonene	Thiophene, 3-methyl-	Quinoline, 1,2-dihydro-2,2,4-trimethyl-
Cyclobutane, (1-methylethylidene)-	Benzo[thiazole], 2-methyl-	Benzene, 1-ethyl-3-methyl-	D-Limonene	Undecane, 2,6-dimethyl-
1-Decene	Cyclohexanone	Benzene, chloro-	Undecane	Tridecane

High risk

Medium risk

Low risk

Slight risk

Figure 8. Risk classification of the pollutants.

It can be found in Figure 9 that hazardous index associated with DS CRA 20% and CRA 50% are significantly higher than those associated with CRA 30%, CRA 40%, and CRA 50%. The fume probably released by DS CRA 20% and CRA 50% will have a more deleterious effect on human health than those released by CRA 30%, CRA 40%, and CRA 50%. The release of fumes is primarily influenced by temperature. At elevated temperatures, the release of more harmful substances is essentially inevitable. However, the impact of temperature on the hazardousness of different crumb rubber-modified asphalt is not uniform. The data indicate that temperature has a significant impact on the hazard posed by crumb rubber-modified asphalt, with a notable increase in risk observed between 120 °C and 170 °C for DS CRA 20% and between 170 °C and 185 °C for CRA 50%.

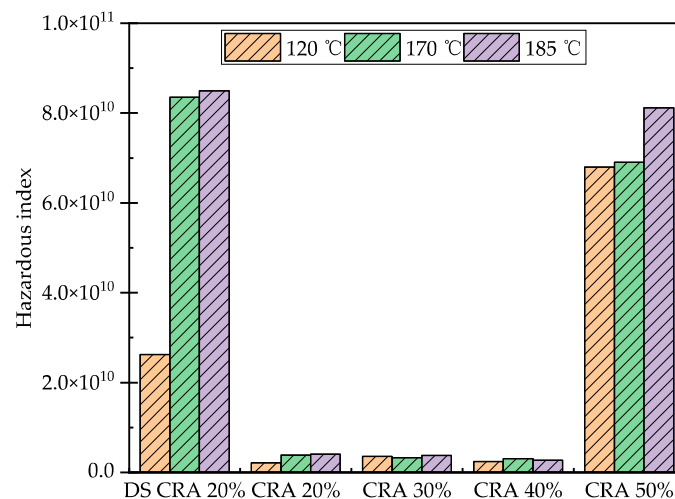


Figure 9. Hazardous index of crumb rubber-modified asphalt.

3.2. Micro-Morphology Characteristics of Inhibition Materials

Figure 10 shows SEM results of kaolin powder (KL) and expanded graphite powder (EG). The magnifications of 1000, 10,000, and 50,000 were used for observation, respectively. As shown in Figure 10, expanded graphite mainly consists of a larger flake morphology, and under the observation of 50 k magnifications, it can be found that its microstructure still mainly consists of a flake structure with a lot of powder particles attached to its surface. The kaolin powder consists of extremely fine dispersed particles, and after 50 k

magnification, it can be found that its microstructure is still composed of fine particles combined, constituting a pore structure of many sizes.

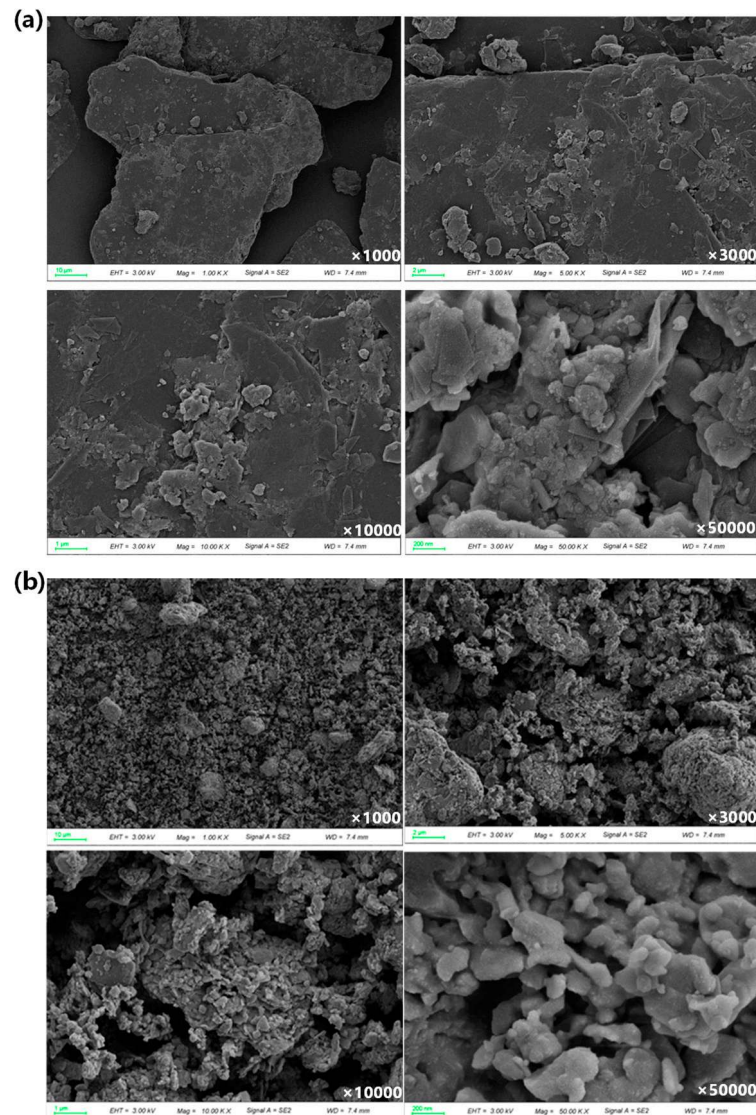


Figure 10. Micro-morphology under different magnifications: (a) EG and (b) KL.

The pore characteristics and surface area of EG and KL are shown in Figure 11. The specific surface area of kaolin is much larger than that of expanded graphite due to the small powder particles and complex structure. But expanded graphite mainly consists of larger flake morphology and the pore structure is not obvious, so the specific surface area is reduced. Meanwhile, the microporous area and external pore area per unit mass of kaolin powder are larger than that of expanded graphite; for expanded graphite, the microporous area accounts for a larger proportion of 58.21%, while kaolin powder is dominated by the external pore area, accounting for 55.23%.

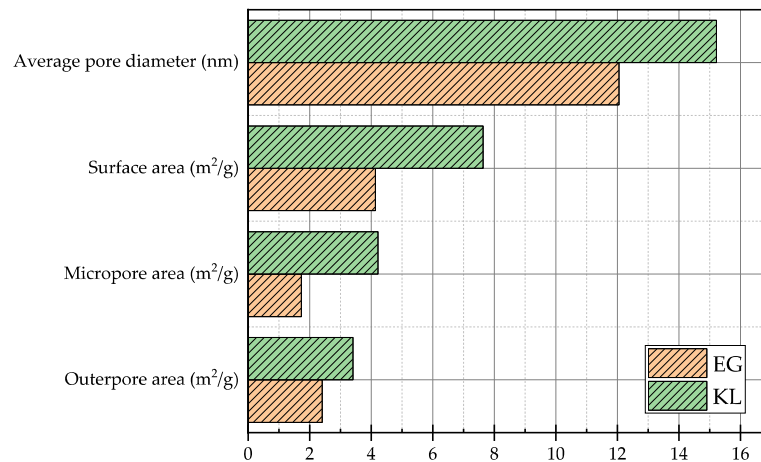


Figure 11. Pore characteristics of inhibition materials.

Figure 12 shows the pore distribution of EG and KL. It can be found that expanded graphite and kaolin have a pore distribution in the range of 1 nm to 120 nm, except for the range of 3.5–7 nm. The pore volume of kaolin powder is better overall than that of expanded graphite, and its pore structure is significantly larger than that of expanded graphite in both the ranges of 1–2 nm and 7–120 nm, while expanded graphite is slightly better than kaolinite powder in the range of 2–3 nm. Expanded graphite is mainly dominated by flake structure; its specific surface area is relatively small, and the area of micropores in it accounts for a large proportion, while kaolin powder is composed of fine particles, its specific surface area is larger, and the area of external pores is predominant. The combination of the two materials, flake and powder particles, constitutes the result of flakes and fine particles dispersed in the bitumen, with the potential for the synergistic adsorption of fumes.

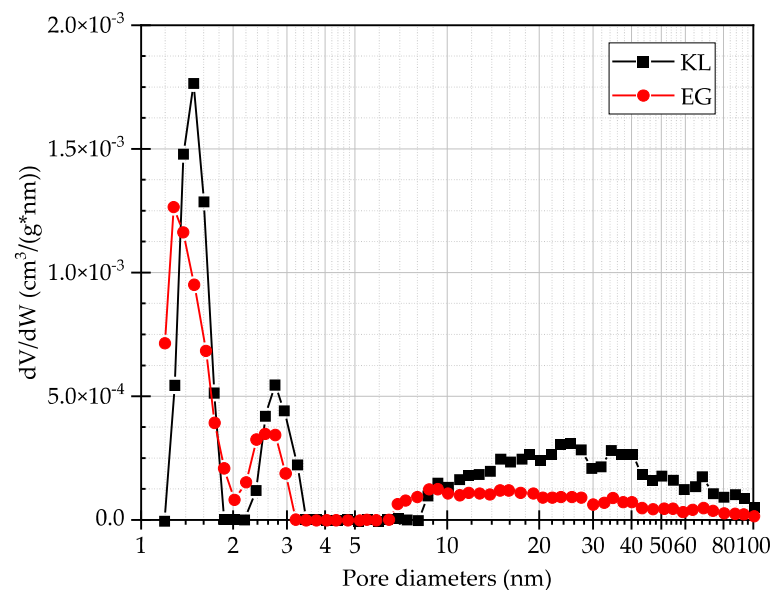


Figure 12. Pore distribution of inhibition materials.

3.3. Evaluation of Emission of Inhibited Crumb Rubber-Modified Asphalt

The released result of inhibited CRA 40% crumb rubber-modified asphalt is shown in Figure 13. The inhibition formulas all have an inhibitory effect on VOCs. The VOC inhibition effect is not obvious at 120 °C, but it is significant at 170 °C and 185 °C. The inhibition effect on CRA 40%-KL6% was weak, while CRA 40%-EG6% and CRA 40%-EG3%-KL3% have obvious inhibition effects, and the former has a better VOC inhibition effect. Figure 13b shows the inhibition effect on the release of NO. Compared with CRA

40%, the release of CRA 40%-EG6% and CRA 40%-KL6% increased at 185 °C. The addition of expanded graphite increased the NO release of CRA 40% by 2.39 times, while kaolinite powder increased it by 1.67 times. However, CRA 40%-EG3%-KL3% completely inhibited the release of NO. Compared with CRA 40%, CRA 40%-KL6% increased the SO₂ emission at 170 °C, but the other two proportions did not promote the SO₂ emission from crumb rubber-modified asphalt. Figure 13d shows the inhibition effect on the release of H₂S. Compared with CRA 40%, CRA 40%-EG6% and CRA 40%-KL6% both increased the release at 185 °C. The addition of expanded graphite increased the release of CRA 40% by 11.1 times, while kaolin powder increased it by 7.5 times. However, CRA 40%-EG3%-KL3% completely inhibited H₂S.

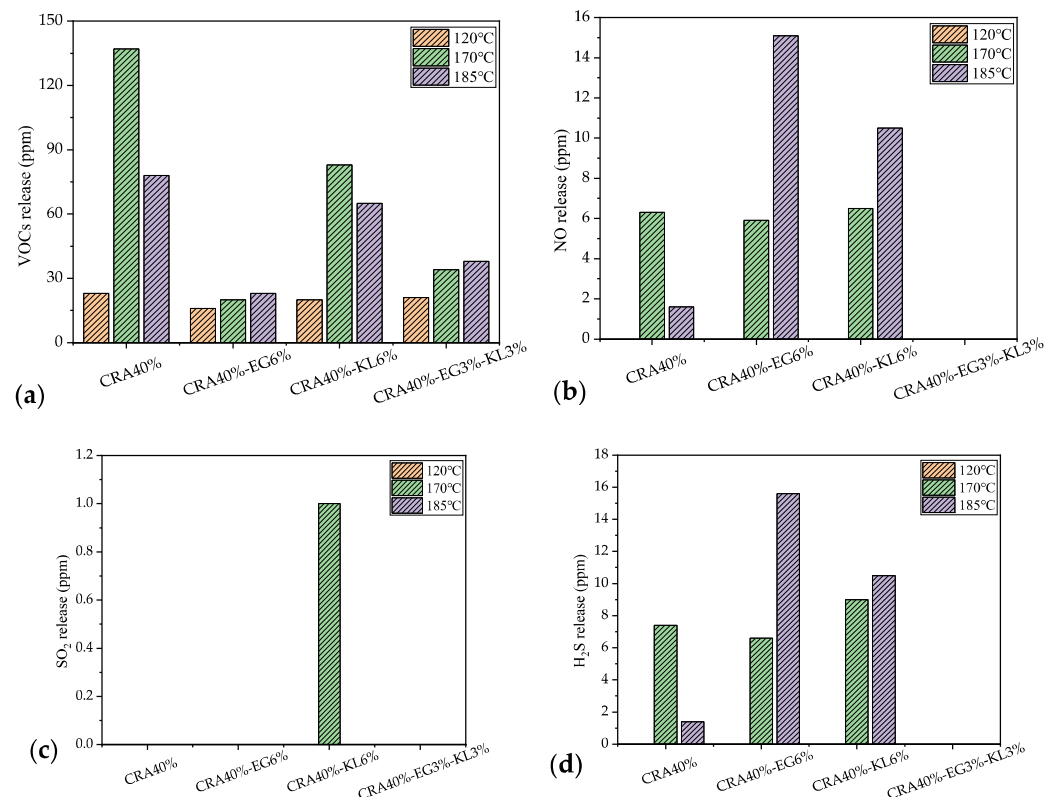


Figure 13. Release of gas from inhibited crumb rubber-modified asphalt at different temperatures: (a) VOCs, (b) NO, (c) SO₂, and (d) H₂S.

Figure 14 shows the release of particulate matter from inhibited crumb rubber-modified asphalt at different temperatures. It can be found that 6% expanded graphite significantly inhibited the emission of PM 1.0 at 170 °C by 5.65 times, significantly increased emission at 120 °C by 5.68 times, and had almost no inhibition effect on the emission at 185 °C. However, 6% kaolin inhibited nearly half of the emission at 170 °C and increased the emission at 185 °C and 120 °C by more than 3 times. The mixed combination significantly inhibited the emission at 170 °C and 185 °C by 74.6% and 95.2% but increased the emission at 120 °C by 11.1 times. As shown in Figure 14b, 6% expanded graphite slightly inhibited the PM 2.5 emission at 170 °C by 42% and at 185 °C by 15% but significantly increased the emission at 120 °C. Further, 6% kaolin slightly inhibited the emission at 170 °C by 27% but significantly increased the emission at 185 °C and 120 °C. The mixed combination significantly inhibited the emission at 170 °C and 185 °C by 74.6% and 95.2% but greatly increased the emission at 120 °C. Figure 14c shows that the release of PM 10.0. 6% expanded graphite inhibited the emission at 185 °C by 21%, increased the emission at 170 °C by 34%, but significantly increased the emission at 120 °C. Moreover, 6% kaolin slightly increased the emission at temperatures. The mixed combination significantly inhibited the emission

at 185 °C by 96.6% but greatly increased the emission at 120 °C and 170 °C. It can be found that the inhibition materials can reduce the release of some pollutants, but, at the same time, promote the release of NO and H₂S. As for particulate matter, the inhibition materials increase the release at 120 °C and have a certain control effect on the release at 170 °C and 185 °C. Given the above results, it can be found that the mixed combination can control VOCs, NO, and H₂S well and effectively inhibit the release of various types of particulate matter at 185 °C.

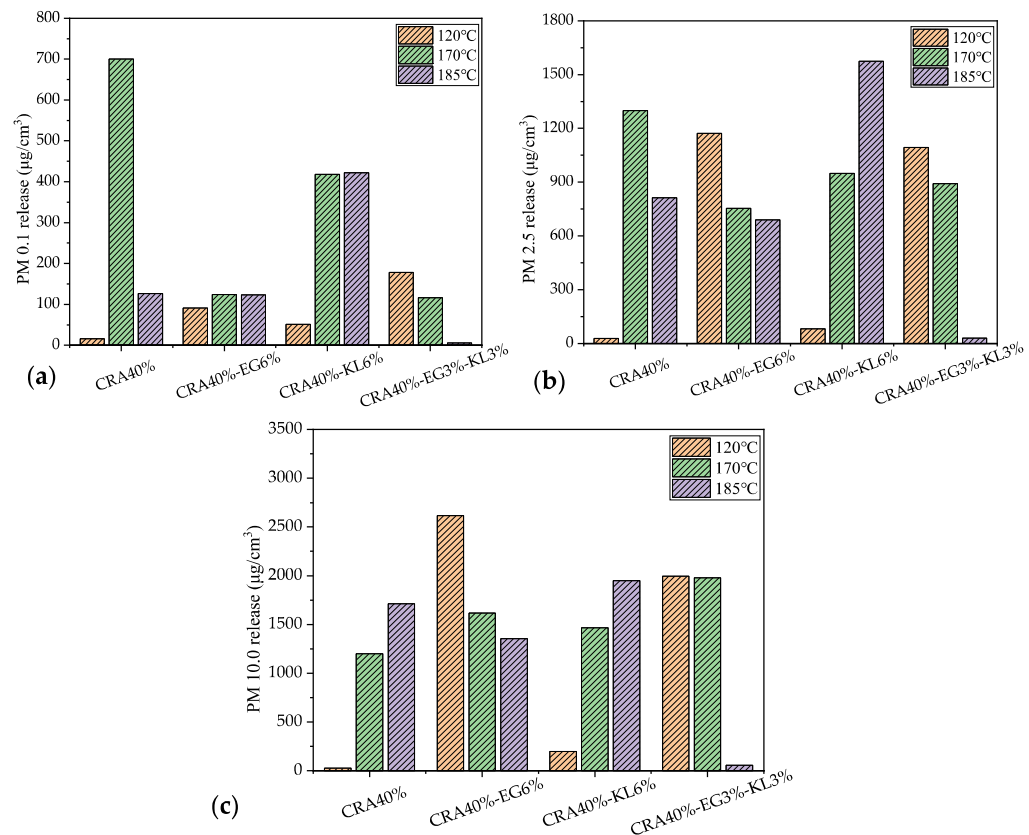


Figure 14. Releases of particulate matter from inhibited crumb rubber-modified asphalt at different temperatures: (a) PM 1.0, (b) PM 2.5, and (c) PM 10.0.

3.4. Optimization of the Inhibition Materials Based on Emission and Rheology

To further optimize the formula of inhibition materials, CRA 40%-EG2%-KL2% and CRA 40%-EG1%-KL1% were prepared, and their emission was also tested. The results are shown in Figure 15. It can be found that the three groups of materials all have similar inhibitory effects on VOCs and can completely inhibit NO and H₂S without prompting CRA to generate SO₂ by 40%.

As shown in Figure 16, for particulate matter, CRA 40%-EG3%-KL3% inhibited the release of PM 1.0 and PM 2.5 at 170 °C and 185 °C, but, at the same time, led to many PM 1.0, PM 2.5 and PM 10.0 at 120 °C. The release of CRA 40%-EG1%-KL1% was like that of CRA 40%, which inhibited the production of PM 1.0 and PM 2.5 at 170 °C. However, CRA 40%-EG2%-KL2% slightly inhibited the release of PM 1.0, PM 2.5, and PM 10.0 at 170 °C and 185 °C and appropriately increased the release of particulate matter at 120 °C, with the effects in the range of CRA 40%-EG3%-KL3% and CRA 40%-EG1%-KL1%.

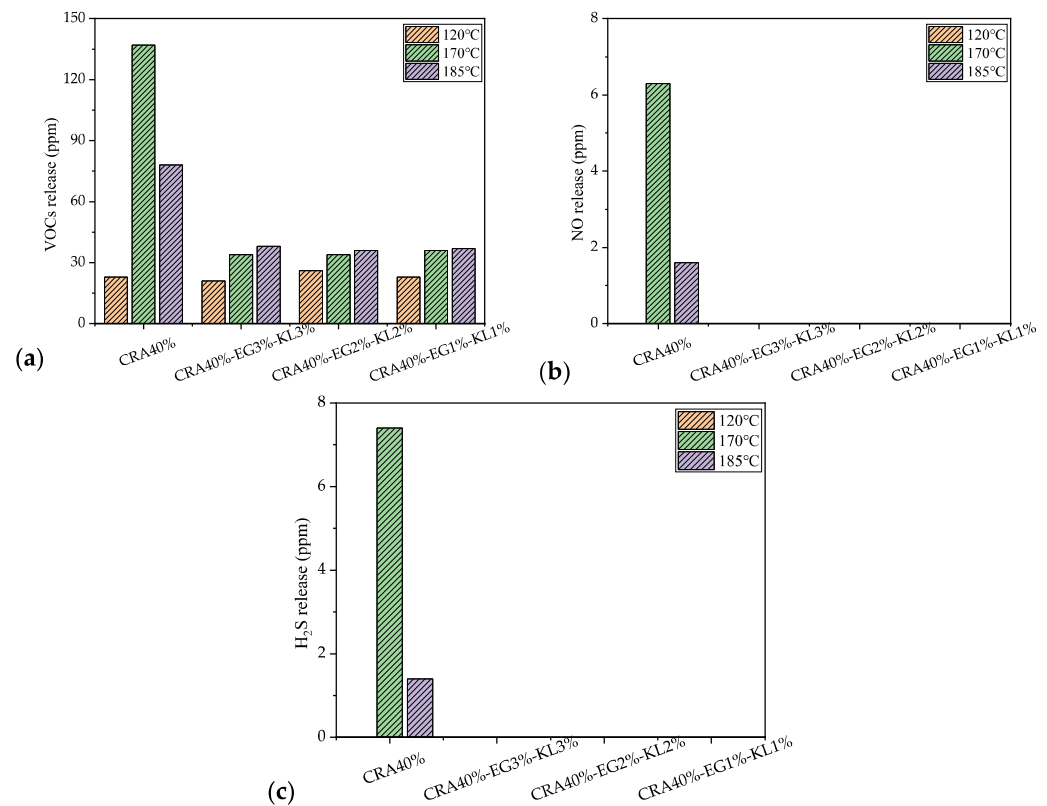


Figure 15. Release of gas from inhibited crumb rubber-modified asphalt with optimized formula at different temperatures: (a) VOCs, (b) NO, and (c) SO₂.

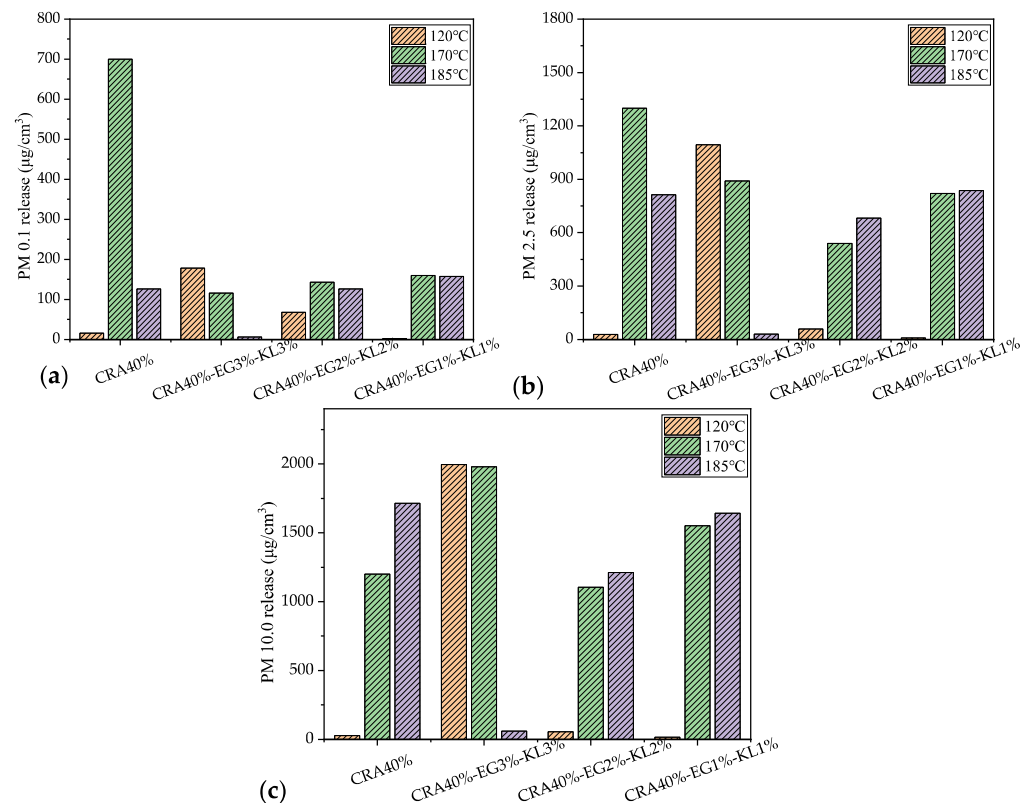


Figure 16. Releases of particulate matter from inhibited crumb rubber-modified asphalt with optimized formula at different temperatures: (a) PM 1.0, (b) PM 2.5, and (c) PM 10.0.

As shown in Figure 17, the complex modulus and phase angle of crumb rubber-modified asphalt were obtained. It can be found that the phase angle of the asphalts with the optimized formula was observed to be higher than CRA 40% at all temperatures. This indicates that the adhesion of the crumb rubber-modified asphalt with 40% rubber powder blending was enhanced by the addition of the inhibition materials. The addition of kaolin powder resulted in a notable enhancement in the adhesion of crumb rubber-modified asphalt across all temperature conditions. CRA 40%-EG6% demonstrated relatively high viscoelasticity at whole temperature conditions. CRA 40%-EG2%-KL2% had the next highest performance, while CRA 40%-EG1%-KL1% exhibited the lowest viscosity.

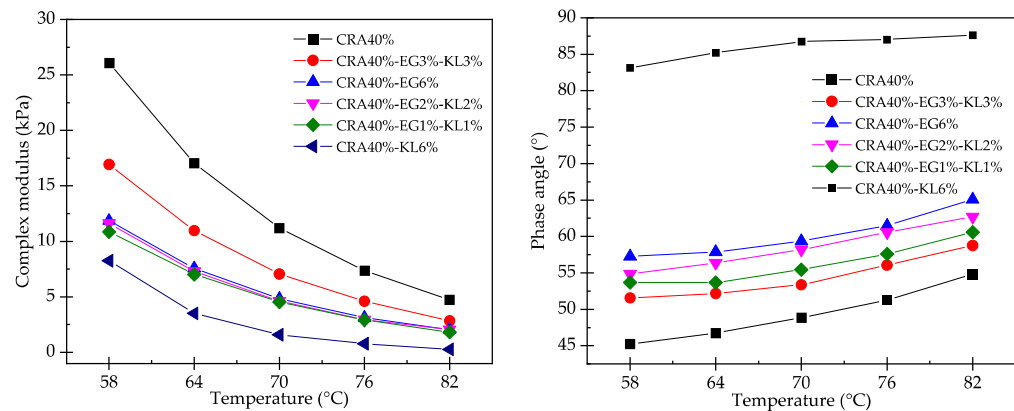


Figure 17. Complex modulus and phase angle of crumb rubber-modified asphalt with different inhibition formulas at different temperatures.

Figure 18 illustrates the rutting factor of crumb rubber-modified asphalt with different inhibition formulas at different temperatures. The results indicate that CRA 40% exhibits the greatest rutting resistance at all temperatures, suggesting that the rutting resistance of CRA 40% was reduced after the additions. CRA 40%-EG6% exhibited better rutting resistance across the five temperature conditions. CRA 40%-EG2%-KL2% demonstrated the next highest level of resistance, while CRA 40%-EG1%-KL1% exhibited the lowest rutting resistance. In general, the combination had some impacts on the rheological performance of CRA 40%. The combination of CRA 40%-KL6% exhibited the best adhesion but also demonstrated the poorest rutting resistance. The composite CRA 40%-EG3%-KL3% exhibited the optimal rutting resistance, although it also demonstrated the lowest viscosity.

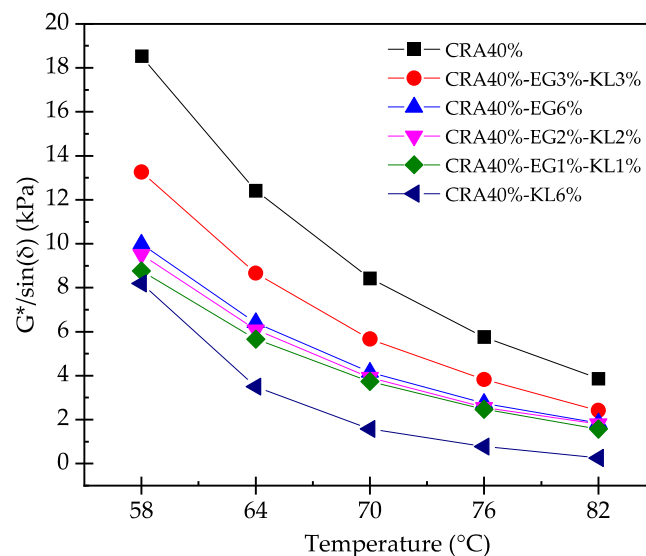


Figure 18. Rutting factors of crumb rubber-modified asphalt with different inhibition formulas.

With the emission and rheological properties considered together, it can be concluded that CRA 40%-EG2%-KL2% displays superior characteristics in terms of adhesion and rutting resistance. Considering the evaluation results in fume suppression, coupled with the cost implications of incorporating additional materials, CRA 40%-EG2%-KL2% was identified as the optimal fume suppression ratio. This ratio was demonstrated to effectively suppress VOCs by 53.8–75.2% while simultaneously preventing the release of NO and H₂S. This resulted in the prompt release of SO₂ from CRA 40% while simultaneously inhibiting PM1.0 by 79.6%, PM2.5 by 58.46%, and PM10.0 by 58.46% under conditions of 185 °C.

4. Conclusions

This study investigated the emission risk of asphalt fume from crumb rubber-modified asphalt and inhibition technology using the combination of EG and KL. The main conclusions are as follows:

1. Crumb rubber-modified asphalt produces an increased asphalt fume with temperature increasing. The release of VOCs exhibited a general increase with more rubber powder content. DS CRA 20% resulted in a reduction in the release of H₂S and NO, while only CRA 50% resulted in the release of SO₂ above 170 °C.
2. The most significant pollutants released from crumb rubber-modified asphalt are p-xylene, toluene, and benzene. Benzothiazole, naphthalene, and other potential carcinogens at elevated temperatures were observed. DS CRA 20% and CRA 50% have severe potential health effects on workers and their surroundings.
3. The inhibition materials based on kaolin and expanded graphite can inhibit the release of certain pollutants. CRA 40%-EG3%-KL3% was effective in controlling the release of VOCs, NO, and H₂S in asphalt. Furthermore, the combination did not promote the production of SO₂ and effectively inhibited the release of various particles at 185 °C.
4. Considering emission, rheological properties, and cost, CRA 40%-EG2%-KL2% was determined as the optimization formula. This ratio was found to effectively inhibit VOCs by 53.8% to 75.2%. It can completely inhibit the release of NO and H₂S while also preventing the promotion of SO₂ release by CRA 40% and significantly inhibit the release of particulate matter.

Author Contributions: Z.W.: Conceptualization, Methodology, Project Administration, Supervision, and Writing—Original Draft. H.L.: Conceptualization, Investigation, and Data Curation. M.J.: Methodology, Data Curation, and Writing—Review and Editing. Q.D.: Conceptualization and Methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by the Science and Technology Cooperation project of Hebei Tonghua Highway Material Co., Ltd. (WHLG-DTXJ-21121501), the Hebei Provincial Communication Department project (No. YC-201926), the China Communications Construction Group Co., Ltd. Science and Technology R&D Project (No. 2021KJW02), and Taizhou CCCC First Highway Engineering Construction Co., Ltd. (No. JGKT-202201).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: Zipeng Wang was employed by the Hebei Transportation Investment Group Company Limited, Shijiazhuang and Hebei Tonghua Highway Materials Co. Ltd. Qunle Du was employed by the Hebei Transportation Investment Group Company Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Cui, P.; Wu, S.; Xiao, Y.; Hu, R.; Yang, T. Environmental Performance and Functional Analysis of Chip Seals with Recycled Basic Oxygen Furnace Slag as Aggregate. *J. Hazard. Mater.* **2021**, *405*, 124441. [CrossRef] [PubMed]
2. EAPA. Manifesto of the European Asphalt Pavement Association on the Occasion of Its 50th Anniversary 1973–2023. Available online: <https://eapa.org/eapa-manifesto-2023-view/> (accessed on 14 July 2024).
3. Xu, H.; Zou, Y.; Airey, G.; Wang, H.; Zhang, H.; Wu, S.; Chen, A. Wetting of Bio-Rejuvenator Nanodroplets on Bitumen: A Molecular Dynamics Investigation. *J. Clean. Prod.* **2024**, *444*, 141140. [CrossRef]
4. Yang, C.; Wu, S.; Cui, P.; Amirkhanian, S.; Zhao, Z.; Wang, F.; Zhang, L.; Wei, M.; Zhou, X.; Xie, J. Performance Characterization and Enhancement Mechanism of Recycled Asphalt Mixtures Involving High RAP Content and Steel Slag. *J. Clean. Prod.* **2022**, *336*, 130484. [CrossRef]
5. Cao, Z.; Chen, M.; Han, X.; Wang, R.; Yu, J.; Xu, X.; Xue, L. Influence of Characteristics of Recycling Agent on the Early and Long-Term Performance of Regenerated SBS Modified Bitumen. *Constr. Build. Mater.* **2020**, *237*, 117631. [CrossRef]
6. Gao, B.; Zhao, Y.; Zhao, Z. Characteristics of Polyurethane/Waste Rubber Powder Composite Modifier and Its Effect on the Performance of Asphalt Mixture. *Sustainability* **2023**, *15*, 12703. [CrossRef]
7. Wang, Y.; Qiao, J.; Li, G.; Chen, Z.; Tan, Y.; Cong, X.; Dong, Y.; Xiao, S. Effect of Styrene-Butadiene Rubber on Asphalt Binder Energy at Different Temperatures Based on Molecular Dynamics Simulation. *J. Mater. Civ. Eng.* **2024**, *36*, 04023539. [CrossRef]
8. Yang, F.; Hu, Z.; Xi, H. Comparative Investigation on the Properties and Molecular Mechanisms of Natural Phenolic Compounds and Rubber Polymers to Inhibit Oxidative Aging of Asphalt Binders. *Adv. Mater. Sci. Eng.* **2022**, *2022*, 5700516. [CrossRef]
9. Gao, M.; Chen, Y.; Fan, C.; Li, M. Molecular Dynamics Study on the Compatibility of Asphalt and Rubber Powder with Different Component Contents. *ACS OMEGA* **2022**, *7*, 36157–36164. [CrossRef]
10. Zhao, Z.; Wu, S.; Xie, J.; Yang, C.; Wang, F.; Li, N.; Liu, Q.; Amirkhanian, S. Effect of Direct Addition of Asphalt Rubber Pellets on Mixing, Performance and VOCs of Asphalt Mixtures. *Constr. Build. Mater.* **2024**, *411*, 134494. [CrossRef]
11. Zhang, X.; Tang, B.; Yang, X.; Li, J.; Cao, X.; Zhu, H. Risk Assessment of Volatile Organic Compounds from Aged Asphalt: Implications for Environment and Human Health. *J. Clean. Prod.* **2024**, *440*, 141001. [CrossRef]
12. Cui, P.; Schito, G.; Cui, Q. VOC Emissions from Asphalt Pavement and Health Risks to Construction Workers. *J. Clean. Prod.* **2020**, *244*, 118757. [CrossRef]
13. Wang, M.; Wang, C.; Huang, S.; Yuan, H. Study on Asphalt Volatile Organic Compounds Emission Reduction: A State-of-the-Art Review. *J. Clean. Prod.* **2021**, *318*, 128596. [CrossRef]
14. Wu, R.; Xiao, Y.; Zhang, P.; Lin, J.; Cheng, G.; Chen, Z.; Yu, R. Asphalt VOCs Reduction of Zeolite Synthesized from Solid Wastes of Red Mud and Steel Slag. *J. Clean. Prod.* **2022**, *345*, 131078. [CrossRef]
15. Li, N.; Jiang, Q.; Wang, F.; Xie, J.; Li, Y.; Li, J.; Wu, S. Emission Behavior, Environmental Impact and Priority-Controlled Pollutants Assessment of Volatile Organic Compounds (VOCs) during Asphalt Pavement Construction Based on Laboratory Experiment. *J. Hazard. Mater.* **2020**, *398*, 122904. [CrossRef] [PubMed]
16. Lv, Y.; Wu, S.; Li, N.; Cui, P.; Wang, H.; Amirkhanian, S.; Zhao, Z. Performance and VOCs Emission Inhibition of Environmentally Friendly Rubber Modified Asphalt with UiO-66 MOFs. *J. Clean. Prod.* **2023**, *385*, 135633. [CrossRef]
17. Anthonissen, J.; Van den Bergh, W.; Braet, J. Review and Environmental Impact Assessment of Green Technologies for Base Courses in Bituminous Pavements. *Environ. Impact Assess. Rev.* **2016**, *60*, 139–147. [CrossRef]
18. Li, X.; Wu, S.; Wang, F.; You, L.; Yang, C.; Cui, P.; Zhang, X. Quantitative Assessments of GHG and VOCs Emissions of Asphalt Pavement Contained Steel Slag. *Constr. Build. Mater.* **2023**, *369*, 130606. [CrossRef]
19. Xie, J.; Ding, Z.; Luo, H.; Zhao, X.; Li, S.; Ma, Y. Interaction of Composite Fume Suppression and Odor Elimination Agents with Crumb Rubber Modified Asphalt: Inhibition Behavior of Volatile Organic Compounds (VOCs) and Inorganic Fume. *Sci. Total Environ.* **2024**, *935*, 173459. [CrossRef]
20. Zhang, J.; Chen, M.; Wu, S.; Zhou, X.; Zhao, G.; Zhao, Y.; Cheng, M. Evaluation of VOCs Inhibited Effects and Rheological Properties of Asphalt with High-Content Waste Rubber Powder. *Constr. Build. Mater.* **2021**, *300*, 124320. [CrossRef]
21. Chang, X.; Xiao, Y.; Long, Y.; Wang, F.; You, Z. Temperature Dependency of VOCs Release Characteristics of Asphalt Materials under Varying Test Conditions. *J. Traffic Transp. Eng. Engl. Ed.* **2022**, *9*, 280–292. [CrossRef]
22. Zhou, B.; Gong, G.; Liu, Y.; Guo, M.; Wang, C. Technical and Environmental Performance Assessment of VOCs Inhibited Asphalt Binders and Mixtures. *Transp. Res. Part D Transp. Environ.* **2023**, *124*, 103931. [CrossRef]
23. Li, H.; Zhang, Y.; Zhou, L.; Feng, Z.; Sun, J.; Hao, G.; Li, Z. Effect of Rubber Powder Desulfurization on the Compatibility between Rubber and Bitumen: Combination and Insight of Experiments and Molecular Dynamics Simulation. *Constr. Build. Mater.* **2024**, *414*, 134966. [CrossRef]
24. Li, L.; Zhou, T.; Cao, L.; Zhou, J.; Liu, Z.; Dong, Z. Characterization of Emissions from Rubber Modified Asphalt and Their Impact on Environmental Burden: Insights into Composition Variability and Hazard Assessment. *J. Hazard. Mater.* **2024**, *477*, 135336. [CrossRef] [PubMed]
25. Kang, B.; Qi, C.; Han, S.; Kuang, D.; Wu, Y.; Chen, H.; Zhang, H.; Xuan, W. Characterization of De-Crosslinking Crumb Rubber on Mechano-Chemical Recovery for Asphalt Performance Improvement. *Constr. Build. Mater.* **2024**, *426*, 136161. [CrossRef]
26. Wang, Z.; Zhao, Z.; Yang, C.; Yang, X.; Chen, S.; Zou, Y. Performance Evaluation of Asphalt Modified with Steel Slag Powder and Waste Tire Rubber Compounds. *Sustainability* **2022**, *14*, 8615. [CrossRef]

27. Xing, B.; Feng, Y.; Sun, S.; Qian, C.; Fang, C.; Lv, X.; Song, A.; Lyu, Y. Investigations on the Rheological and Swelling-Degradation Behavior of Crumb Rubber within the Bituminous Matrix. *Constr. Build. Mater.* **2023**, *367*, 130262. [\[CrossRef\]](#)
28. Wang, Z.; Wu, S.; Yang, C.; Xie, J.; Xiao, Y.; Zhao, Z.; Wang, F.; Zhang, L. Quantitative Assessment of Road Performance of Recycled Asphalt Mixtures Incorporated with Steel Slag. *Materials* **2022**, *15*, 5005. [\[CrossRef\]](#)
29. Mousavi, M.; Park, K.-B.; Kim, J.-S.; Fini, E.H. Metal-Rich Biochar as an Asphalt Modifier to Improve Sustainability and Reduce VOC Emissions. *Sustain. Mater. Technol.* **2024**, *40*, e00903. [\[CrossRef\]](#)
30. Dong, R.; Zhang, Z.; Zhou, T.; Deng, W.; You, H. Research on the Fatigue Properties of Rejuvenated Asphalt Prepared by Waste Cooking Oil Pre-Desulfurized Crumb Tire Rubber. *Polymers* **2023**, *15*, 740. [\[CrossRef\]](#)
31. Huang, Z.; Guan, B.; Li, P.; Liu, T.; Ma, X.; Xiong, R.; Nian, J.; Li, J. Degradation Performance and Mechanism of VOCs in Asphalt by Alkali Metal-Doped La₂Ce₂O₇-Based Fluorite through Pyroelectric and Photocatalytic Synergy. *Constr. Build. Mater.* **2024**, *443*, 137842. [\[CrossRef\]](#)
32. Jiang, Q.; Li, N.; Yang, F.; Ren, Y.; Wu, S.; Wang, F.; Xie, J. Rheology and Volatile Organic Compounds Characteristics of Warm-Mix Flame Retardant Asphalt. *Constr. Build. Mater.* **2021**, *298*, 123691. [\[CrossRef\]](#)
33. Chang, X.; Wan, L.; Long, Y.; Xiao, Y.; Xue, Y. Optimal Zeolite Structure Design for VOC Emission Reduction in Asphalt Materials. *Constr. Build. Mater.* **2023**, *366*, 130227. [\[CrossRef\]](#)
34. Tang, N.; Yang, K.; Alrefaei, Y.; Dai, J.-G.; Wu, L.-M.; Wang, Q. Reduce VOCs and PM Emissions of Warm-Mix Asphalt Using Geopolymer Additives. *Constr. Build. Mater.* **2020**, *244*, 118338. [\[CrossRef\]](#)
35. Espinoza, J.; Medina, C.; Calabi-Floody, A.; Sanchez-Alonso, E.; Valdes, G.; Quiroz, A. Evaluation of Reductions in Fume Emissions (VOCs and SVOCs) from Warm Mix Asphalt Incorporating Natural Zeolite and Reclaimed Asphalt Pavement for Sustainable Pavements. *Sustainability* **2020**, *12*, 9546. [\[CrossRef\]](#)
36. Ge, L.; Yao, Y.; Xu, L.; Zhou, Z.; Li, J.; Zhang, X.; Liu, C.; Lv, H. Mitigation of Asphalt Volatile Organic Compounds Emissions and Health Hazards Using a TiO₂-Doped Biochar Composite: Microscopic and Physiological Insights. *Environ. Technol. Innov.* **2024**, *36*, 103763. [\[CrossRef\]](#)
37. Jin, J.; Liu, S.; Zhang, B.; Qian, G.; Gao, Y.; Li, R. Effects of G-C₃N₄/MMT Composite on High Rheological Behaviors and Catalytic Properties of Asphalt. *J. Mater. Civ. Eng.* **2024**, *36*, 04024242. [\[CrossRef\]](#)
38. Cao, Z.; Gong, G.; Liu, Y.; Cao, X.; Tang, B.; Wang, C. Effects of Different Inhibitors on Emission Characteristics, Environmental Impact and Health Risk of Volatile Organic Compounds from Asphalt Binder. *J. Clean. Prod.* **2023**, *428*, 139427. [\[CrossRef\]](#)
39. Wei, M.; Wu, S.; Zhu, L.; Li, N.; Yang, C. Environmental Impact on VOCs Emission of a Recycled Asphalt Mixture with a High Percentage of RAP. *Materials* **2021**, *14*, 947. [\[CrossRef\]](#)
40. Wang, Q.; Zhang, Y.; Hussain, A.; Guo, Z.; Wang, L.; Cui, Y. Asphalt-Derived Hierarchical Porous Carbon as an Efficient Adsorbent for Benzene. *Sep. Purif. Technol.* **2025**, *353*, 128467. [\[CrossRef\]](#)
41. Mo, S.; Wang, Y.; Xiong, F.; Ai, C.; Wang, D.; Tan, G.Y.A. Changes of Asphalt Fumes in Hot-Mix Asphalt Pavement Recycling. *J. Clean. Prod.* **2020**, *258*, 120586. [\[CrossRef\]](#)
42. Lv, Y.; Wu, S.; Li, N.; Cui, P.; Liu, Q.; Amirkhanian, S. Screening and Environmental Risk Assessment of VOCs Preferential Pollutants in Net Flavor Rubber-Modified Asphalt Based on the Information Entropy Method. *Constr. Build. Mater.* **2024**, *420*, 135616. [\[CrossRef\]](#)
43. Zhang, X.; Tang, B.; Cao, X.; Li, J.; Zhu, H. Study on the Release Characteristics of Volatile Organic Compounds from Different Aged Asphalt. *J. Clean. Prod.* **2023**, *423*, 138774. [\[CrossRef\]](#)
44. Ministry of Transport of the People's Republic of China. *Technical Specification for Construction of Highway Asphalt Pavements*; Ministry of Transport of the People's Republic of China: Beijing, China, 2004.
45. Li, H.; Jia, M.; Zhang, X.; Wang, Z.; Liu, Y.; Yang, J.; Yang, B.; Sun, Y.; Wang, H.; Ma, H. Laboratory Investigation on Fumes Generated by Different Modified Asphalt Binders. *Transp. Res. Part D Transp. Environ.* **2023**, *121*, 103828. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.