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Original Research Article

Detection and Analysis of Gas Emissions Based on Recycled Maintenance Technology

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Abstract: This study focuses on the green maintenance technology using 60% RAP plant-mix hot recycling, aiming to reveal the emission characteristics of asphalt mixtures with different gradations in road green maintenance and support low-carbon transportation infrastructure. Three asphalt mixtures, GAC-13, SMA-13 and GAC-20, were tested. Emissions of VOCs, inorganic gases and particulate matter during production and construction were monitored. Summa canisters with GC-MS, flue gas analyzers and filter membrane gravimetric methods were adopted for pollutant measurement. Results show that under 60% RAP hot recycling, SMA-13 emits more alkanes and amines than GAC-13 and GAC-20 at both construction sites and mixing plants. For CO_2 and particulate matter, emissions at construction sites and mixing plants both follow the order SMA-13 > GAC-13 > GAC-20. These findings clarify the gaseous emission differences among gradations and provide data support for low-carbon road maintenance technology selection and emission control.

Keywords: Road Maintenance; Asphalt Mixture; Gas Emission.

1. Introduction

As global climate governance continues to deepen, carbon peaking and carbon neutrality have evolved into core strategies for China's ecological civilization construction and high-quality development.[1-4]. China has formally established a "1+N" policy framework, with the *Action Plan for Carbon Peaking Before 2030* as the top-level guideline to comprehensively drive the green and low-carbon transition in key sectors such as transportation, urban and rural construction, and industrial production. Since the 14th Five-Year Plan period, the country has steadily promoted the shift from "dual control of energy consumption" to "dual control of total carbon emissions and carbon emission intensity". It clearly stipulates that energy conservation and carbon reduction should be implemented across the full life cycle of transportation infrastructure construction, integrating carbon emission management into the entire process of engineering construction, material production, construction, as well as operation and maintenance.[5-8].

As a key component of transportation infrastructure, road engineering involves concentrated energy consumption and carbon emissions during asphalt mixture mixing, transportation, paving and other processes, accompanied by emissions of organic waste gas, particulate matter and other pollutants[9,10]. Coordinated pollution reduction and carbon reduction have thus become an inevitable requirement for the industry. Driven by both mandatory policy constraints and green development goals, research on carbon emission and pollutant emission characteristics of asphalt mixtures with different gradations, combined with the life cycle assessment (LCA) method, and the selection of low-emission and low-energy-consumption materials and technologies are of great practical significance and engineering value for achieving national dual carbon goals, promoting the green transformation of transportation infrastructure, and supporting the construction of near-zero carbon projects[11-14].

Based on the technological characteristics of green projects, methods for the collection, detection and evaluation of asphalt fumes at construction sites are proposed[15]. This green maintenance project covers 11 green technologies, including clean in-place hot recycling of materials, integrated mixing and paving equipment, insulated bins for clean construction, on-site equipment for adding reclaimed or new materials, high-content plant-mix hot recycling technology, application of non-tracking emulsified asphalt, high-performance epoxy plant-mix hot recycled asphalt mixture, plant-mix hot recycling equipment, and high-content plant-mix hot recycled green maintenance technology. In-depth investigation of these processes and materials enables targeted development of asphalt fume collection, detection and evaluation methods, providing a scientific basis for evaluating the green performance of the project[16-21].

Asphalt fumes are generated during the production and construction of asphalt mixtures. They mainly consist of volatile organic compounds (VOCs), inorganic components such as carbon oxides and nitrogen oxides, as well as aerosol particulate matter (PM). Asphalt fumes not only pose a severe threat to the health and safety of on-site construction workers but also exert long-term adverse impacts on the ecological environment [22-25]. Therefore, to evaluate the environmental performance of the project, this study employs a comprehensive assessment method for asphalt fumes to conduct an in-depth investigation into their composition and concentration levels.

2. VOCs

2.1 Monitoring Indicators of VOCs

VOCs, or volatile organic compounds, denote a class of organic compounds characterized by high saturated vapor pressure (>13.33 Pa), low boiling points, small molecular weights, and strong volatility under standard ambient temperature and pressure. The monitoring indicators in this section focus on VOCs emissions during the mixture production and construction phases of the green maintenance technology using plant-mix hot recycling. Specifically, they include VOCs emissions from three types of asphalt mixtures, namely SMA-13, GAC-13 and GAC-20, during the production and construction stages under the 60% RAP plant-mix hot recycling condition.

2.2 VOCs Monitoring Equipment and Protocol

In this project, asphalt fumes were collected using Summa canisters and analyzed with an Agilent GC-MS system. During monitoring, asphalt fumes were collected in Summa canisters and pretreated using a three-stage cryogenic trap atmospheric pre-concentration system. A 400 mL sample was concentrated for analysis, and 50 mL of internal standard gas was added before rapid heating for injection into the Agilent GC-MS. Separation was performed using gas chromatography, and qualitative and quantitative analysis was carried out via mass spectrometry. The pretreatment and analytical instruments used were an atmospheric pre-concentrator manufactured by ENTECH (USA) and a gas chromatography-mass spectrometry system manufactured by Agilent. The equipment is shown in Figure 2.1, and the operating parameters of the GC-MS are listed in Table 2.1.

Table 2.1 Operating Parameters of GC-MS System

Instrument Type	Item	Analysis Conditions
Gas Chromatography	Capillary Column	DB-5MS column (60 m × 320 μm × 1 μm)
	Column Flow Rate	2.0ml/min
	Inlet Temperature	150 °C; split injection, split ratio 20:1, split flow 40 mL/min
	Temperature Program	Initial temperature 35 °C, hold for 5 min; rise to 140 °C at 6 °C/min; then rise to 220 °C at 15 °C/min and hold for 5 min
Mass Spectrometry	Scan Mode	Full scan mode
	Mass Range	30~300amu
	Ionization Energy	70eV
	Interface Temperature	250°C
	Ion Source Temperature	230°C

Figure 2.1 Agilent GC-MS (Gas Chromatography-Mass Spectrometer)

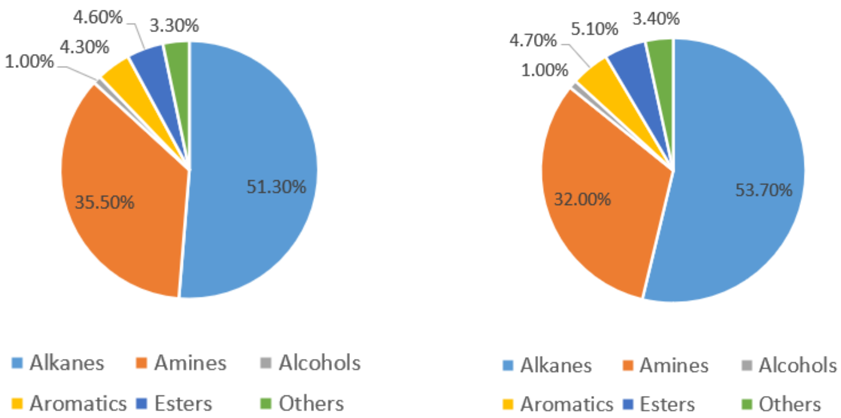
2.3 Analysis of VOCs Monitoring Results

2.3.1 Comparative Analysis of VOCs Concentrations in 60% RAP Plant-Mix Hot Recycling

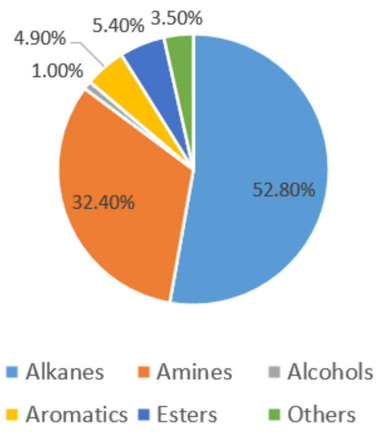
This project monitored the VOCs concentrations of three types of plant-mix hot recycled asphalt materials (60% RAP), namely SMA-13, GAC-13 and GAC-20, at both the construction site and the mixing plant. The researchers ranked the compounds from high to low according to their concentrations and selected those accounting for the top 80% of the total concentration for analysis and comparison. These compounds were classified by functional groups into six categories: alkanes, amines, alcohols, aromatic hydrocarbons, esters, and others.

Comparative Analysis of VOCs Concentrations at Construction Sites

A total of 235 volatile organic compounds were detected at the construction site of SMA-13, 244 at the construction site of GAC-13, and 240 at the construction site of GAC-20. The proportions of various compounds are shown in Figure 2.2(a), Figure 2.2(b) and Figure 2.2(c), respectively. It can be seen from the figures that alkanes account for the highest proportion in SMA-13, reaching 51.3%, followed by amines at 35.5%, while the proportions of other compounds are all less than 10%. For GAC-13, alkanes also account for the highest proportion at 53.7%, followed by amines at 32.0%, with other compounds each accounting for less than 10%. In GAC-20, alkanes account for 52.8%, the highest proportion, followed by amines at 32.4%, and the remaining compounds each account for less than 10%.



(a) **(b)**



(c)

Figure 2.2 (a) Proportion of Volatile Organic Compounds at SMA-13 Construction Site; (b) Proportion of Volatile Organic Compounds at GAC-13 Construction Site; (c) Proportion of Volatile Organic Compounds at GAC-20 Construction Site

The researchers analyzed the concentrations of various compounds at the construction sites of SMA-13, GAC-13 and GAC-20 produced by the 60% RAP plant-mix hot recycling technology, and their comparison is shown in Figure 2.3. It can be seen from the figure that the total emissions of alkanes and amines at the SMA-13 construction site are higher than those of GAC-13 and GAC-20 by 10.1% and 13.1% respectively.

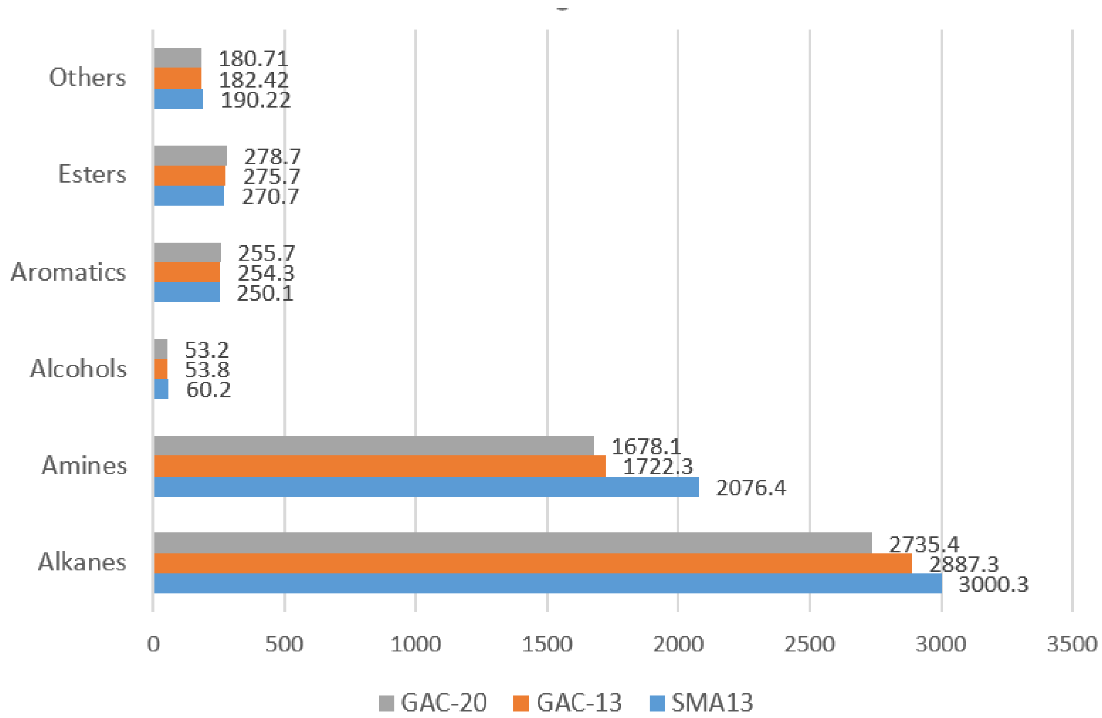
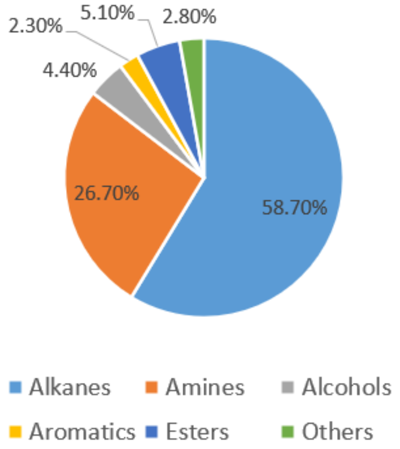


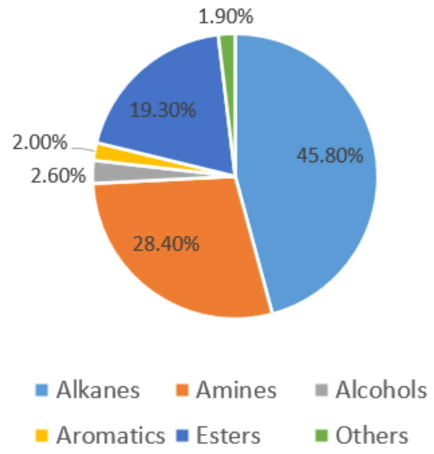
Figure 2.3 Concentrations of Volatile Organic Compounds at Construction Sites of SMA-13, GAC-13 and GAC-20 (μg/m³)

Comparative Analysis of VOCs Concentrations at the Mixing Plant

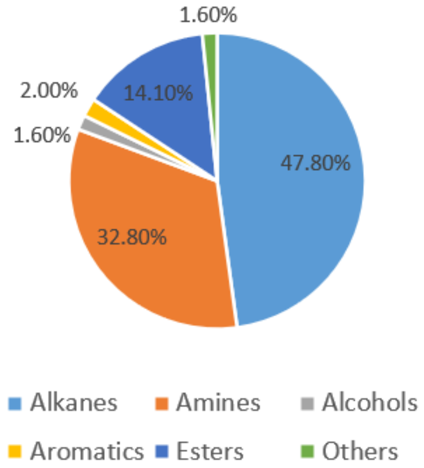
A total of 219 volatile organic compounds were detected at the mixing plant of SMA-13, 228 at the mixing plant of GAC-13, and 230 at the construction site of GAC-20. The researchers ranked the VOCs in descending order of concentration and selected the compounds accounting for the top 80% of the total concentration for classification. The proportions of each compound category are shown in Figure 2.4(a), Figure 2.4(b) and Figure 2.4(c). It can be seen from the figures that in SMA-13, alkanes account for the highest proportion at 58.7%, followed by amines at 26.7%, with all other compounds accounting for less than 10%. In GAC-13, alkanes also account for the largest proportion at 45.8%, followed by amines at 28.4%, while the proportions of other compounds are all below 10%. For GAC-20, alkanes constitute the highest proportion at 47.8%, followed by amines at 32.8%, and the remaining compound categories each account for less than 10%.



(a)



(b)



(c)

Figure 2.4 (a) Proportion of Volatile Organic Compounds at SMA-13 Mixing Plant; (b) Proportion of Volatile Organic Compounds at GAC-13 Mixing Plant; (c) Proportion of Volatile Organic Compounds at GAC-20 Mixing Plant

The researchers analyzed the concentrations of various compounds at the mixing plants of SMA-13, GAC-13 and GAC-20, and their comparison is shown in Figure 2.5 It can be seen from the figure that the total emissions of alkanes and amines at the SMA-13 mixing plant are higher than those of GAC-13 and GAC-20 by 11.2% and 4.8% respectively.

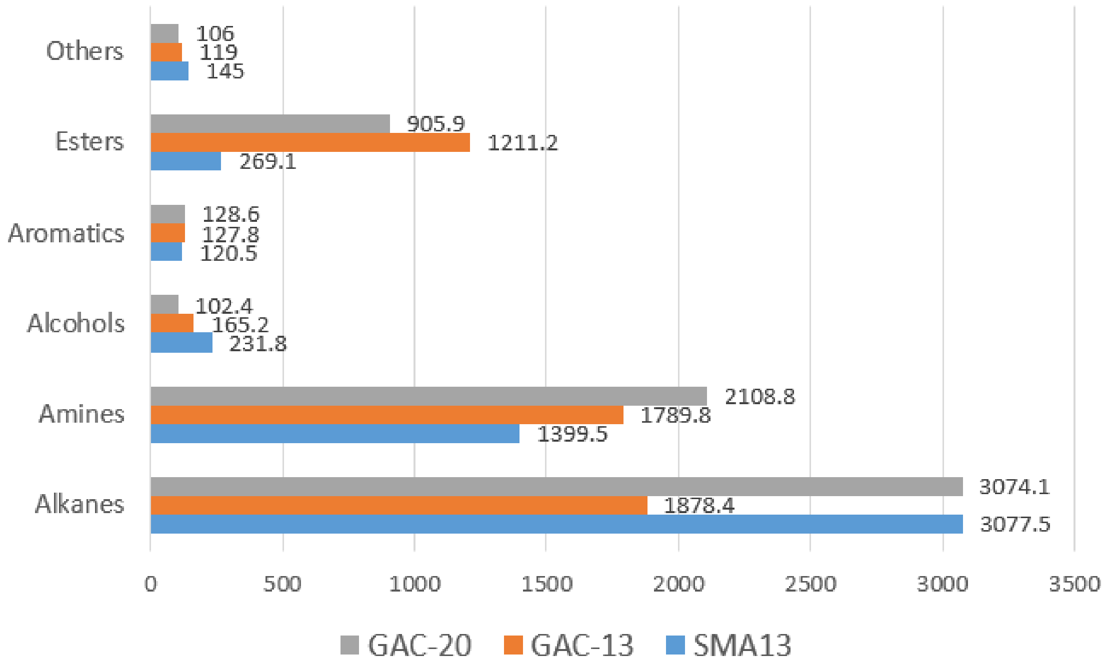


Figure 2.5 Concentrations of Volatile Organic Compounds at Mixing Plants of SMA-13, GAC-13 and GAC-20 (μg/m³)

3. Inorganic Gases

3.1 Inorganic Gas Monitoring Indicators

In this section, the monitoring indicators cover the emissions of four inorganic gases, namely CO_2, CO, NO, and NO_2, during the mixture production and construction phases of two green maintenance technologies: in-place hot recycling and plant-mix hot recycling. Specifically, this includes inorganic gas emissions during the production and construction stages of three asphalt mixtures (SMA-13, GAC-13, and GAC-20) under the 60% RAP plant-mix hot recycling condition.

3.2 Inorganic Gas Monitoring Equipment and Scheme

In this project, monitoring was carried out using an intelligent flue gas analyzer and a high-precision nitrogen dioxide flue gas analyzer. The inhaled gas concentration information was converted into electrical signals, and the magnitude of the detected gas concentration was reflected by measuring the intensity of these electrical signals, thus realizing the detection of the target gases. The operating parameters of the two flue gas analyzers are shown in Table 3.1, and the instruments are presented in Figure 3.1(a) and Figure 3.1(b).

Table 3.1 Operating Parameters of GC-MS System

Gas Name	Measurement Range (ppm)	Resolution (ppm)	Response Time (s)
Carbon Monoxide	0~2000	0.1	<60
Nitrogen Dioxide	0~1000	0.1	<60
Sulfur Dioxide	0~2000	0.1	<60

(a) (b)

Figure 3.1 (a) Nitrogen Dioxide Flue Gas Analyzer; (b) Intelligent Smoke and Flue Gas Analyzer

3.3 Analysis of Inorganic Gas Monitoring Results

To comprehensively monitor the inorganic gases emitted by recycled asphalt mixture during the paving process, a total of 8 monitoring points were set up at the pavement maintenance site to measure inorganic gas emissions from asphalt mixture, including the paver, SMA-13 60% mixing plant, SMA-13 60% front site, GAC-13 60% mixing plant, GAC-13 60% front site, GAC-20 60% mixing plant, and GAC-20 60% rear site. The statistical table of inorganic gas emission monitoring data at the pavement maintenance site is shown in Table 3.2.

Table 3.2 Statistical Table of Inorganic Gas Monitoring Data Volume

Monitoring Point	Paver (ppm)	SMA-13 60% Mixing Plant (ppm)	SMA-13 60% Front Site (ppm)	GAC-13 60% Mixing Plant (ppm)	GAC-13 60% Front Site (ppm)	GAC-20 60% Mixing Plant (ppm)	GAC-20 60% Front Site (ppm)
CO2	420	640	620	480	475	460	450
CO	ND1	ND	ND	ND	ND	ND	ND
NO	ND	ND	ND	ND	ND	ND	ND
NO2	0.22	ND	0.052	ND	0.045	ND	0.031

[1] *ND indicates that the inorganic gas was not detected, or the detected concentration was below the detection limit.

3.3.1 Comparative Analysis of Inorganic Gas Concentrations for 60% RAP Plant-Mixed Hot Recycling

This project monitored the inorganic gas concentrations of three asphalt materials, namely 60% RAP plant-mixed hot recycled SMA-13, GAC-13 and GAC-20. The monitoring sites were the construction site and the mixing plant, and the inorganic gases included CO_2, CO, NO and NO_2.

Comparative Analysis of Inorganic Gas Concentrations at Construction Site

At the construction site of plant-mixed hot recycling (60% RAP) SMA-13, two inorganic gases, CO_2 and NO_2, were detected with concentrations of 620 ppm and 0.052 ppm, respectively. For plant-mixed hot recycling (60% RAP) GAC-13, CO_2 and NO_2 were also identified at the construction site, with concentrations of 475 ppm and 0.045 ppm, respectively. As for plant-mixed hot recycling (60% RAP) GAC-20, the two detected inorganic gases at the construction site were CO_2 and NO_2, with concentrations of 450 ppm and 0.031 ppm, respectively. The CO_2 concentration of GAC-

13 60% was 5.6% higher than that of GAC-20 60%, and the CO_2 concentration of SMA-13 60% was 31% higher than that of GAC-13 60%. SMA-13 60% exhibited the highest CO_2 concentration, while GAC-20 60% showed the lowest.

Comparative Analysis of Inorganic Gas Concentrations at Mixing Plants

Only one inorganic gas, CO_2, was detected at the mixing plant for SMA-13 60%, with a concentration of 640 ppm. Similarly, only CO_2 was identified at the mixing plant for GAC-13 60%, at a concentration of 480 ppm, and at the mixing plant for GAC-20 60%, at a concentration of 460 ppm. The CO_2 concentration at the GAC-13 60% mixing plant was 4.3% higher than that at the GAC-20 mixing plant. The CO_2 concentration at the SMA-13 60% mixing plant was 33.3% higher than that at the GAC-13 mixing plant. The SMA-13 60% mixing plant had the highest CO_2 concentration, while the GAC-20 60% mixing plant had the lowest.

4.Particulate Matter

4.1 Comparative Analysis of Inorganic Gas Concentrations at Mixing Plants

The monitoring indicators in this section focus on particulate matter emissions from two green maintenance technologies, namely hot in-place recycling and plant-mixed hot recycling, during both mixture production and construction stages. Specifically, they include particulate matter emissions during the production and construction phases of three asphalt mixtures, SMA-13, GAC-13, and GAC-20, under the 60% RAP plant-mixed hot recycling condition.

4.2 Particulate Matter Monitoring Equipment and Scheme

Particulate matter in the flue gas was collected and enriched using a 0.2 μm PTFE hydrophobic filter membrane holder connected to an air sampling pump. Following moisture removal from the particulate matter captured on the filter membrane, the asphalt fume concentration was determined based on the mass gain of the filter membrane before and after sampling. To guarantee test accuracy, the filter membrane was first dried in an oven at 100 °C for 2 hours to eliminate moisture and then stored in a desiccator prior to use. After sampling, the loaded filter membrane was removed and placed in a desiccator to equilibrate for 72 hours, allowing adsorbed water vapor to be fully removed. The particulate matter monitoring setup is illustrated in Figure 4.1.

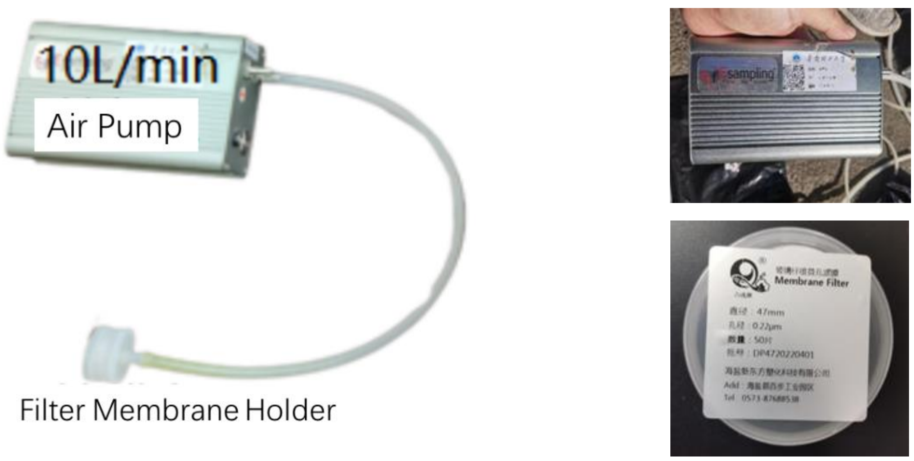


Figure 4.1. Schematic Diagram of Particulate Matter Monitoring Equipment

4.3 Analysis of Particulate Matter Monitoring Results

4.3.1 Comparative Analysis of Particulate Matter Concentrations in 60% RAP Plant-Mixed Hot Recycling

This project monitored the particulate matter concentrations of three asphalt materials, namely 60% RAP plant-mixed hot recycled SMA-13, GAC-13 and GAC-20, at the construction site and the mixing plant respectively.

Comparative Analysis of Particulate Matter Concentrations at Construction Site

The particulate matter concentrations at the construction sites for plant-mixed hot recycled (60% RAP) SMA-13, GAC-13 and GAC-20 are shown in Figure 4.2. It can be seen from the figure that the particulate matter concentrations are 0.4 μg/m³, 0.31 μg/m³ and 0.3 μg/m³ respectively.

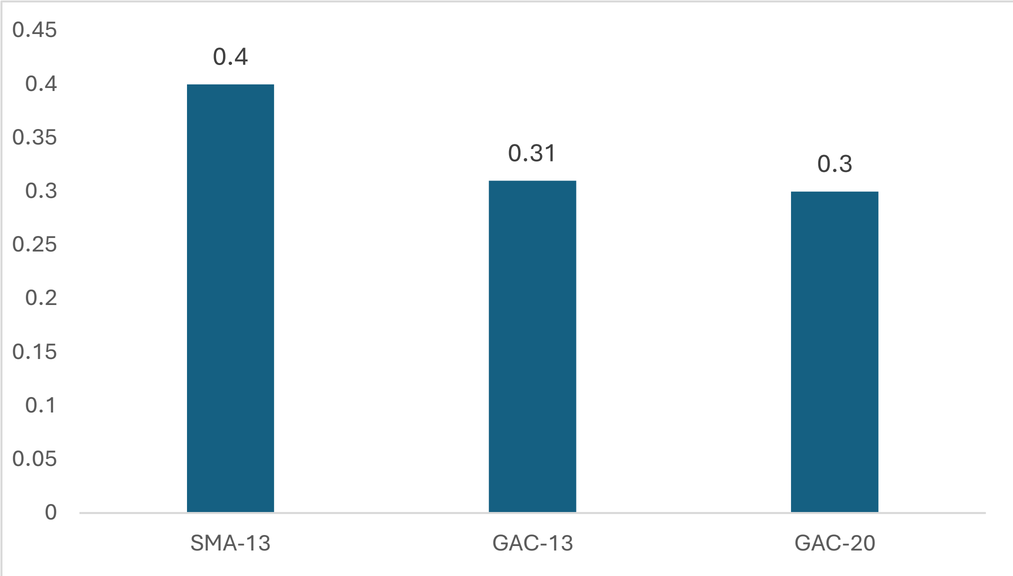


Figure 4.2 Particulate Matter Concentrations at Different Asphalt Construction Sites (μg /m³)

Comparative Analysis of Particulate Matter Concentrations at Mixing Plants

The particulate matter concentrations at the mixing plants for plant-mixed hot recycled (60% RAP) SMA-13, GAC-13 and GAC-20 are shown in Figure 4.3. It can be seen from the figure that the particulate matter concentration at the SMA-13 mixing plant is 132.3 μg/m³, that at the GAC-13 mixing plant is 122.4 μg/m³, and that at the GAC-20 mixing plant is 119.8 μg/m³. The particulate matter concentration at the GAC-13 mixing plant is 2.2% higher than that at the GAC-20 mixing plant, and the concentration at the SMA-13 mixing plant is 8% higher than that at the GAC-13 mixing plant. The SMA-13 mixing plant exhibits the highest particulate matter concentration, while the GAC-20 mixing plant shows the lowest.

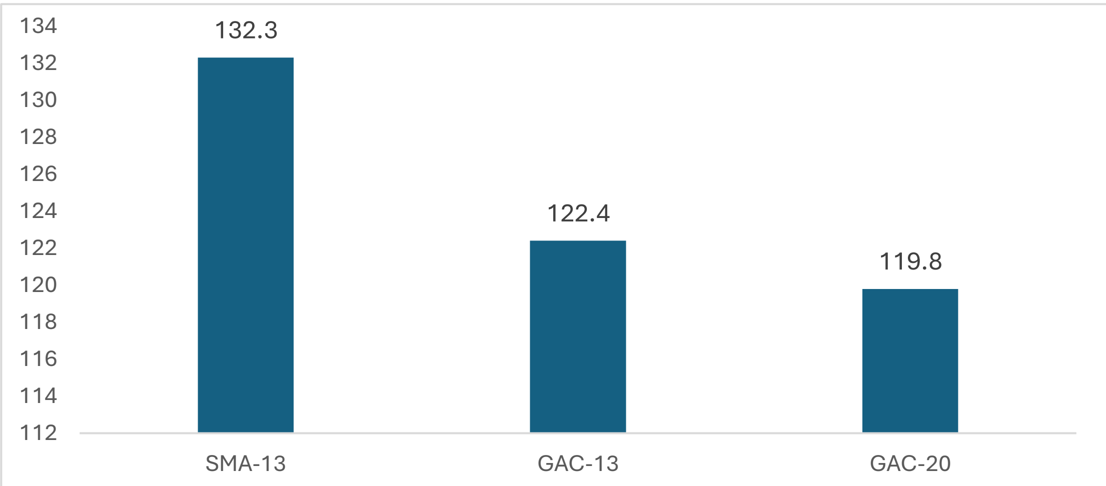


Figure 4.3 Particulate Matter Concentrations at Different Asphalt Mixing Plants (μg/m³)

5.Results

Under the 60% RAP plant-mixed hot recycling technology, the total emissions of alkanes and amines from SMA-13 at the construction site were 10.1% and 13.1% higher than those of GAC-13 and GAC-20, respectively. The total emissions of alkanes and amines from SMA-13 at the mixing plant were 11.2% and 4.8% higher than those of GAC-13 and GAC-20, respectively. SMA-13 exhibited the highest total emissions of alkanes and amines both at the construction site and the mixing plant.

Under the 60% RAP plant-mixed hot recycling process, the order of CO_2 emissions at the construction site for various asphalt mixtures is SMA-13 > GAC-13 > GAC-20. The order of CO_2 emissions at the mixing plant for various asphalt mixtures is also SMA-13 > GAC-13 > GAC-20. For both the construction site and the mixing plant, SMA-13 shows the highest total CO_2 emissions, while GAC-20 shows the lowest.

Under the 60% RAP plant-mixed hot recycling technology, the order of particulate emissions at the construction site for various asphalt mixtures is SMA-13 > GAC-13 > GAC-20. The order of CO_2 emissions at the mixing plant is also SMA-13 > GAC-13 > GAC-20. For both the construction site and the mixing plant, SMA-13 has the highest total particulate emissions, while GAC-20 has the lowest.

6.Conclusion

This study systematically investigated the emission characteristics of volatile organic compounds (VOCs), inorganic gases, and particulate matter from three asphalt mixtures (SMA-13, GAC-13, and GAC-20) under 60% RAP plant-mix hot recycling technology during both construction site and mixing plant operations. Based on the experimental results and comparative analyses, the following conclusions can be drawn.

Under the 60% RAP plant-mix hot recycling condition, alkanes and amines are the predominant VOCs components emitted from all three asphalt mixtures at both construction sites and mixing plants, collectively accounting for over 75% of total VOCs. SMA-13 exhibits the highest total emissions of alkanes and amines, with emissions at construction sites being 10.1% and 13.1% higher than those of GAC-13 and GAC-20, respectively, and emissions at mixing plants being 11.2% and 4.8% higher, respectively.

Regarding inorganic gas emissions, CO_2 is the primary component detected across all mixtures and monitoring locations, while CO and NO were either undetected or below detection limits. The CO_2 emission order for both construction sites and mixing plants is consistently SMA-13 > GAC-13 > GAC-20. Specifically, the CO_2 concentration of SMA-13 at construction sites is 31% higher than that of GAC-13, while at mixing plants it is 33.3% higher, indicating that SMA-13 has the most significant carbon emission intensity among the three gradations.

For particulate matter emissions, the same order SMA-13 > GAC-13 > GAC-20 is observed at both construction sites and mixing plants. The particulate matter concentration at the SMA-13 mixing plant is 8% higher than that of GAC-13, and the SMA-13 construction site shows the highest particulate emission level at 0.4 $\mu g/m^3$.

Overall, among the three asphalt mixtures evaluated under the 60% RAP plant-mix hot recycling technology, GAC-20 demonstrates the lowest emission levels for VOCs, CO_2, and particulate matter, making it the most environmentally favorable option. SMA-13, despite its superior road performance in certain applications, exhibits the highest pollutant emissions and therefore requires enhanced emission control measures when employed in green maintenance projects. These findings provide critical data support for the selection of low-emission asphalt mixtures and the formulation of targeted emission reduction strategies in low-carbon road maintenance engineering.

6.References

[1] Dong, Z. Y. Z., Xia, C. Y., Fang, K., & Zhang, W. W. (2022). Effect of the carbon emissions trading policy on the co-benefits of carbon emissions reduction and air pollution control. *Energy Policy, 165*.
[2] Li, R. R., Li, L. J., & Wang, Q. (2022). The impact of energy efficiency on carbon emissions: Evidence from the transportation sector in Chinese 30 provinces. *Sustainable Cities and Society, 82*.
[3] Tong, Y. L., Wang, K., Liu, J. Y., et al. (2023). Refined assessment and decomposition analysis of carbon emissions in high-energy intensive industrial sectors in China. *Science of the Total Environment, 872*.
[4] Zhu, T. Y., Liu, X. L., Wang, X. D., & He, H. (2023). Technical development and prospect for collaborative reduction of pollution and carbon emissions from iron and steel industry in China. *Engineering, 31*, 37–49.
[5] Guo, C., Zhang, X. H., Zhao, L., et al. (2024). Building a life cycle carbon emission estimation model based on an early design: 68 case studies from China. *Sustainability, 16*(2).
[6] Li, H., Deng, Q. X., Zhang, J. X., et al. (2019). Environmental impact assessment of transportation infrastructure in the life cycle: Case study of a fast track transportation project in China. *Energies, 12*(6).
[7] Nie, H. Y., Wang, L. Z., & Tian, M. R. (2024). Analysis on determinants of carbon emissions from plaza ground paving during the construction stage based on life cycle assessment. *Scientific Reports, 14*(1).
[8] Tang, D. Z., Gong, X. Y., & Liu, M. L. (2022). The impact of government behaviors on the transition towards carbon neutrality in the construction industry: A perspective of the whole life cycle of buildings. *Frontiers in Environmental Science, 10*.
[9] Kim, B., Lee, H., Park, H., & Kim, H. (2012). Framework for estimating greenhouse gas emissions due to asphalt pavement construction. *Journal of Construction Engineering and Management, 138*(11), 1312–1321.

[10] Yang, W. H., Zhang, Z. H., Yang, X. L., et al. (2025). Characteristics and microscopic mechanisms of smoke emissions of OMMT/SBS-modified asphalt. *Environment International, 195*.

[11] Goglio, P., Williams, A. G., Balta-Ozkan, N., et al. (2020). Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. *Journal of Cleaner Production, 244*.

[12] Strelets, K., Zaborova, D., Kokaya, D., et al. (2025). Building information modeling (BIM)-based building life cycle assessment (LCA) using industry foundation classes (IFC) file format. *Sustainability, 17*(7).

[13] Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135*, 286–301.

[14] Jullien, A., Dauvergne, M., & Cerezo, V. (2014). Environmental assessment of road construction and maintenance policies using LCA. *Transportation Research Part D: Transport and Environment, 29*, 56–65.

[15] Huang, W., Hu, J., & Luo, S. (2024). The technological innovation pathway for green, low-carbon, and durable pavement construction and maintenance. *Science China Technological Sciences, 67*(12), 3959–3961.

[16] Ali, H., & Grzybowski, K. (2012). Life cycle of hot in-place pavement recycling case study. *Transportation Research Record, 2292*, 29–35.

[17] Chen, H. Q., Tang, G., & Wang, X. (2022). Aging characteristics of plant hot-mix recycled asphalt and its induced aging on new asphalt. *Processes, 10*(5).

[18] Ji, Y. C., Wen, S. T., Zhao, Y. B., et al. (2026). Life cycle carbon emissions and performance trade-offs in recycled asphalt pavements for cold regions: A multi-technique optimization framework. *Journal of Material Cycles and Waste Management*.

[19] Shi, Q. Y., Zhou, L. X., & Li, B. (2025). Road performance of hot central plant versus hot in-place recycling asphalt mixtures: A quantitative comparison and adaptability analysis. *Materials, 18*(22).

[20] Xia, X., Zhao, Y. L., & Tang, D. (2025). The state-of-the-art review on the utilization of reclaimed asphalt pavement via hot in-place recycling technology. *Journal of Cleaner Production, 492*.

[21] Xue, Y. H., Liu, C. C., Shi, Q. J., et al. (2024). Road performance and mechanism of hot in-place recycling asphalt mixture modified by direct-to-plant SBS. *Construction and Building Materials, 416*.

[22] Neumeister, C. E., Olsen, L. D., & Dollberg, D. D. (2003). Development of a flow-injection fluorescence method for estimation of total polycyclic aromatic compounds in asphalt fumes. *AIHA Journal, 64*(5), 618–624.

[23] Raulf-Heimsoth, M., Pesch, B., Schott, K., et al. (2007). Irritative effects of fumes and aerosols of bitumen on the airways: Results of a cross-shift study. *Archives of Toxicology, 81*(1), 35–44.

[24] Wang, M., Li, P., Nian, T. F., & Mao, Y. (2021). An overview of studies on the hazards, component analysis and suppression of fumes in asphalt and asphalt mixtures. *Construction and Building Materials, 289*.

[25] Yang, X. L., Wang, G. C., Rong, H. L., et al. (2022). Review of fume-generation mechanism, test methods, and fume suppressants of asphalt materials. *Journal of Cleaner Production, 347*.