

Evaluation of indoor air quality in a laboratory setting during hot mix asphalt production

Avaliação da qualidade do ar interior em ambiente laboratorial durante a produção de misturas asfálticas usinadas a quente

Michael Lima Silva¹, Mauro Felipe Patrício da Costa¹, Cícero Janderson Tavares Neves¹, Rinaldo dos Santos Araújo¹, Lara Sucupira Furtado², Iuri Sidney Bessa², Lucas Feitosa de Albuquerque Lima Babadopulos²

¹Instituto Federal do Ceará, Fortaleza, Ceará, Brasil

²Universidade Federal do Ceará, Fortaleza, Ceará, Brasil

Contact: contatomichaells@gmail.com,  (MLS); mauro.felipe.patricio05@aluno.ifce.edu.br,  (MFPC); academicoifce@gmail.com,  (CJTN); rinaldo@ifce.edu.br,  (RSA); larasfur@gmail.com,  (LSF); iuri@det.ufc.br,  (ISB); babadopulos@ufc.br,  (LFALB)

Submitted:

8 May, 2025

Revised:

15 July, 2025

Accepted for publication:

26 July, 2025

Published:

11 de November de 2025

Associate Editor:

Francisco Thiago Sacramento Aragão,
Universidade Federal do Rio de Janeiro,
Brasil

Keywords:

Laboratory.
Asphalt mixtures.
Air quality.

Palavras-chave:

Laboratório.
Misturas asfálticas.
Qualidade do ar.

DOI: 10.58922/transportes.v33.e3125

ABSTRACT

Maintaining indoor air quality is a critical aspect of human health and occupational well-being, especially since a large portion of human activities takes place in confined environments. This study aimed to characterize the emission of atmospheric pollutants during laboratory-scale asphalt mixture production, in order to generate knowledge about air quality in such settings and contribute with technical information within the Brazilian context. Experimentally, the following environmental parameters were monitored: air temperature, relative humidity, carbon dioxide (CO₂), total suspended particles (TSP), particulate matter of 10 µm (PM₁₀) and 2.5 µm (PM_{2.5}), as well as metals (Ca, Mg, Zn, Ni, V, and Pb) and benzo(a)pyrene. The average concentrations observed during asphalt mixing were: 1153.2 µg/m³ of TSP; 244.0 µg/m³ of PM₁₀; 161.5 µg/m³ of PM_{2.5}; 5.8 ng/m³ of benzo(a)pyrene; 674 ppm of CO₂; 105.8 µg/m³ of calcium (Ca); 63.6 µg/m³ of magnesium (Mg); and 3.81 µg/m³ of zinc (Zn). Lead (Pb), nickel (Ni), and vanadium (V) were not detected in the samples. Overall, the average concentrations of TSP, PM₁₀, PM_{2.5}, benzo(a)pyrene, Ca, Mg, and Zn exceeded the limits established by national and international standards for indoor environments. The findings raise concerns regarding occupational safety and the environmental sustainability of laboratory-scale asphalt production processes, highlighting the need for control measures, continuous use of personal protective equipment, and changes in laboratory practices to mitigate occupational risks.

RESUMO

A manutenção da qualidade do ar interior é um aspecto crítico para a saúde humana e bem-estar ocupacional, especialmente porque grande parte das atividades humanas ocorrem em ambientes confinados. Este trabalho teve como objetivo caracterizar a emissão de poluentes atmosféricos da produção laboratorial de misturas asfálticas, visando gerar conhecimento sobre a qualidade do ar em ambientes laboratoriais dessa natureza e contribuir para a geração de informações técnicas deste cenário no contexto nacional. Experimentalmente, foram monitorados os seguintes parâmetros ambientais: temperatura do ar, umidade relativa do ar, dióxido de carbono (CO₂), partículas totais em suspensão (PTS), materiais de particulados de 10 µm (MP₁₀) e 2,5 µm (MP_{2,5}), além de metais (Ca, Mg, Zn, Ni, V e Pb) e benzo(a)pireno. As concentrações médias encontradas durante as misturas asfálticas foram: 1153,2 µg/m³ de PTS; 244,0 µg/m³ de MP₁₀; 161,5 µg/m³ de MP_{2,5}; 5,8 ng/m³ de benzo(a)pireno; 674 ppm de CO₂; 105,8 µg/m³ de cálcio (Ca); 63,6 µg/m³ de magnésio (Mg) e 3,81 µg/m³ de zinco (Zn). Os elementos chumbo (Pb), níquel (Ni) e vanádio (V) não foram detectados nas amostragens. Em geral, as concentrações médias de PTS, MP₁₀, MP_{2,5}, benzo(a)pireno, Ca, Mg e Zn ultrapassaram os limites estabelecidos pelas normativas nacional e internacional para ambientes interiores. Os resultados encontrados levantam preocupações quanto à segurança ocupacional e à sustentabilidade ambiental dos processos laboratoriais de produção asfáltica, apontando para a necessidade de medidas de controle, uso contínuo de equipamentos de proteção individuais e mudanças nas rotinas laborais para mitigação de riscos ocupacionais.



1. INTRODUCTION

Asphalt pavements are the most widely used paving material worldwide, accounting for approximately 95% of paved roads in Brazil, including both urban streets and highways (Bernucci et al., 2022). Despite their importance, the transportation infrastructure industry generates environmental hazards, particularly regarding air pollution, since various pollutants are emitted during asphalt paving operations (Alcântara et al., 2019). The primary raw material used in this industry is petroleum, which contains aliphatic compounds, cyclic alkanes, aromatic hydrocarbons, polycyclic aromatic compounds, and metals such as iron, nickel, and vanadium (WHO, 2004). From crude oil, Petroleum Asphalt Cement (AC) is derived, composed mainly of carbon and hydrogen, along with a mixture of heteroatoms such as nitrogen, sulfur, metals, and other elements (Bernucci et al., 2022; Wang et al., 2022).

During paving operations, the asphalt concrete used on roads is composed of a mixture of aggregates (typically crushed stone) and AC used as a binder (Tang et al., 2020; Germin-Aizac et al., 2023). Hot mix asphalt production occurs at temperatures around 160 °C to reduce AC viscosity and ensure proper workability for efficient aggregate coating (Alcântara et al., 2019). As a result of this heating, the hydrocarbons present in the asphalt binder are released into the atmosphere in the form of asphalt fumes, which are emitted into the environment and remain airborne. These fumes typically contain pollutants such as particulate matter, organic and inorganic gases (CO₂, SO₂, NO₂), Volatile Organic Compounds (VOCs), and Polycyclic Aromatic Hydrocarbons (PAHs) (Wang et al., 2021). According to Xu et al. (2018), volatile and particulate compounds have carcinogenic potential and may result in significant risks to human health. Moreover, prolonged occupational exposure to PAHs, present in these emissions, has been linked with the development of lung and skin cancer (Jang et al., 2018). Additionally, the presence of heavy metals is concerning because of their toxicity to humans, with chromium, arsenic, cadmium, and nickel being classified as carcinogenic (Suvarapu and Baek, 2017).

On the other hand, although aggregates — which make up 90-95% of the asphalt mixture mass — are often considered motionless, they also contribute to the emission of fine particles and metals. The processing of these materials, involving steps such as storage, handling, screening, drying, and heating (approximately 15 °C above AC temperature), results in the emission of fugitive dust. The resulting particulates remain airborne, constituting a significant source of pollution in the work environment, alongside asphalt mixture production (Alcântara et al., 2023; Kharat, 2022; Bernucci et al., 2022). A study by von Gunten, Konhauser and Alessi (2020) reported that the wear and weathering of mineral aggregates in asphalt mixtures release metals such as lead (Pb), cadmium (Cd), and zinc (Zn) into the environment. Lucas Jr, Babadopulos and Soares (2019) identified that granite aggregates used in such material primarily contain oxides of silicon, aluminum, iron, calcium, and potassium. These findings align with a study by Han, Lee and Baek (2023), who observed that dust generated during asphalt pavement work contains elements such as aluminum, silicon, magnesium, sodium, and potassium — reinforcing the notion that mineral aggregates are key sources of these elements.

Exposure to air pollutants can occur in both outdoor and indoor environments. Indoor pollutant levels may be 2 to 5 times higher than those in outdoor air, which is particularly concerning given that people spend an average of 90% of their time indoors (USEPA, 2024). In 2024, Brazil implemented a regulatory change regarding indoor air quality standards. ANVISA Resolution RE No. 09/2003, which previously defined reference standards for Indoor Air Quality (IAQ), was replaced by the technical standard NBR 17.037 (ABNT, 2023). This updated standard introduces more current criteria, bringing national parameters into alignment with international guidelines and best engineering practices for IAQ.

Air quality in educational environments, particularly in university laboratories, is a growing concern due to the prolonged time students, technicians, and researchers spend in such spaces. In research centers working on asphalt mixtures, there are potential health risks due to exposure to toxic substances found in asphalt. However, the lack of data regarding these impacts renders the problem largely invisible and often neglected, creating uncertainty about the actual health risks involved (Branco et al., 2024; Sandaka, Gouveia and Senger, 2018).

Although the industrial production of asphalt has been widely studied in terms of air quality impacts, there is a clear gap in the characterization of pollutant emissions during laboratory-scale hot mix asphalt production. Mousavi et al. (2024) and Li et al. (2024) indicate that most research focuses on industrial stages or field applications, with little documentation available for emissions from asphalt mixtures in controlled laboratory environments.

Only four studies stand out regarding emissions from laboratory-scale asphalt mixtures: Saleh, Ashour and Moustafa (2006) investigated VOCs, gases (SO_2 , CO_2 , CO , N_2O), particulate matter, and noise in Egypt; Lin, Hung and Leng (2016) analyzed VOCs, PAHs, $\text{PM}_{2.5}$, and noise in Hong Kong; Abdullah et al. (2016) evaluated CO_2 , NO_2 , and NO_x in Malaysia; and Gaudefroy et al. (2022) studied VOCs in bio-recycled asphalt in France. Thus, the present study aims to pioneer, in Brazil, the investigation of air pollutant emissions from hot mix asphalt production in an academic research setting. It seeks to associate the physical characteristics of the laboratory environment and the concentrations of airborne substances with user well-being and occupational health risks, thereby contributing to the systematization of data in this field.

2. MATERIALS AND METHODS

2.1. Monitoring site

The monitoring of emissions generated during the processing of asphalt materials was conducted in a university laboratory specialized in asphalt mixture research. This laboratory is affiliated with the Technological Research Center for Asphalt, located in the city of Fortaleza, Ceara, Brazil. According to the Brazilian Bioclimatic Zoning described in NBR 15220-3/2024, the city is classified within bioclimatic zone 6A – Very hot and humid, with a Mean Dry Bulb Temperature (MDBT) exceeding 27 °C and an average relative humidity above 68% (ABNT, 2024). The laboratory is located inside a building and has only one façade facing the outdoors (west façade), which favors solar incidence during the afternoon and limits natural ventilation due to the obstruction of prevailing winds from the east and southeast directions (Figure 1). The building exterior cladding consists of non-load-bearing ceramic brick masonry walls, finished with cement mortar plaster. The roof is made of a ribbed reinforced concrete slab, with a ceiling height of 5 m. The space includes eight sliding glass windows (0.6 m × 1.2 m), totaling 5.76 m² of natural ventilation and lighting area, as well as two external gates made of galvanized steel sheets (2.0 m × 2.9 m).

Several studies related to infrastructure are conducted in this laboratory environment, such as material characterization, asphalt mixture production, and mechanical testing. The laboratory layout (Figure 2) includes areas designated for laboratory practices as well as study rooms. The monitoring zone contains two split-type air conditioning units (36,000 BTU each) without air renewal, a countertop stove fueled by Liquefied Petroleum Gas (LPG), and four ovens.

The mixer used for asphalt mixture production is located in the central area of the laboratory, positioned in a corridor that connects different operational sectors, such as the screening station and the compaction/simulation station. The space is equipped with an axial-type exhaust system, connected to ducts that discharge fumes to the outside. This system is installed directly above the mixer to remove gases and vapors emitted during the mixing process.

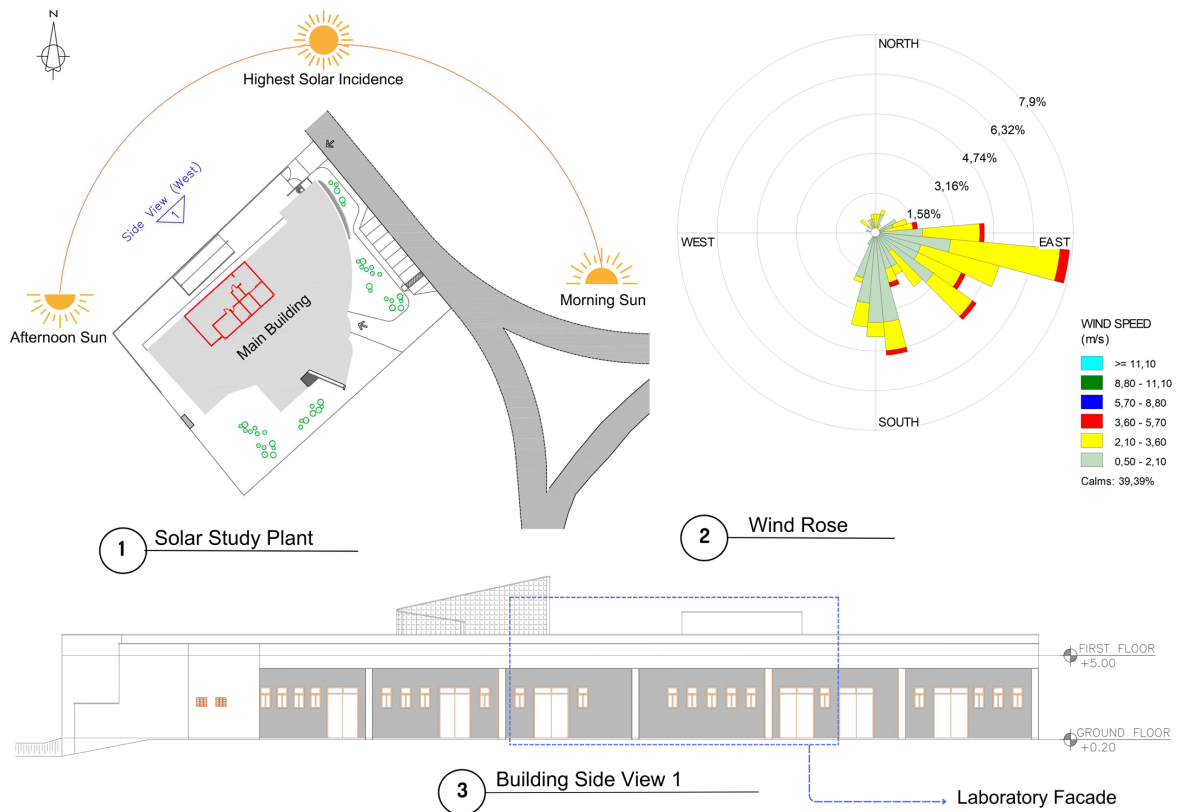


Figure 1. Solar plan of the building with wind rose and side view highlighting the location of the laboratory.

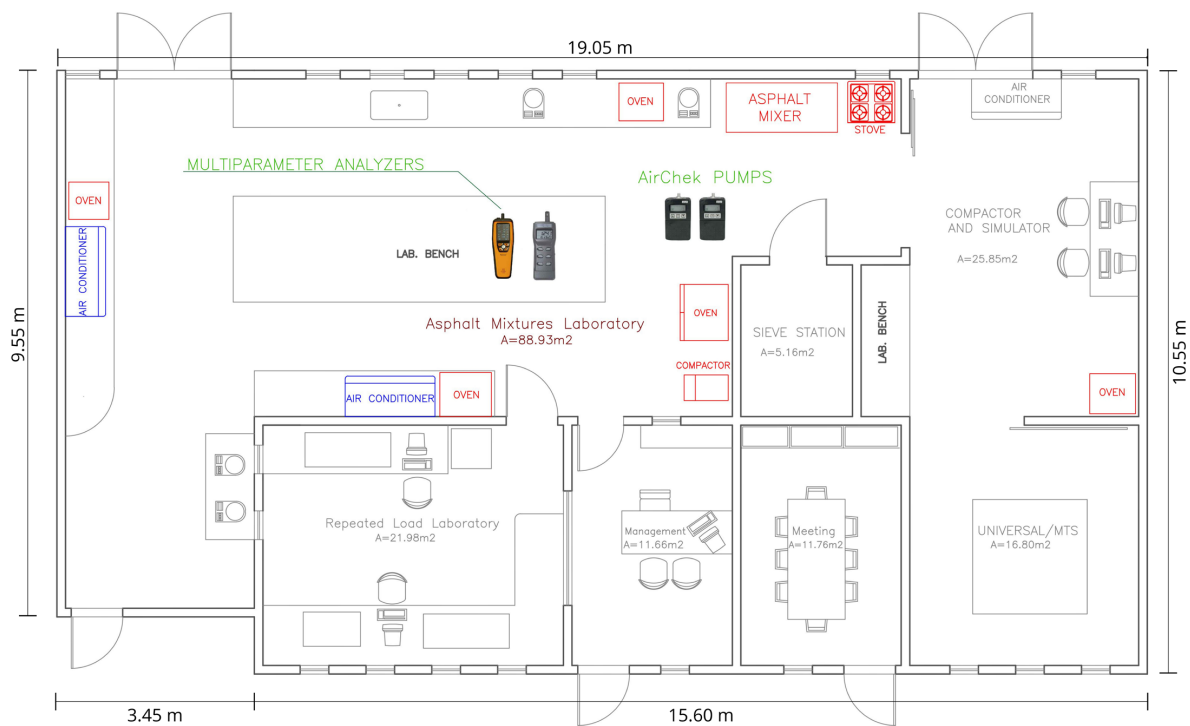


Figure 2. Floor plan of the asphalt mixtures laboratory.

During laboratory activities, two air conditioning units are used to cool the environment. Doors and windows remain constantly closed in order to prevent the dispersion of pollutants to adjacent areas, resulting in the absence of natural ventilation or air exchange with the outdoor space, except when the exhaust system is activated.

This exhaust system is typically used during the production of asphalt mixtures. However, considering that the aim of this study is to characterize atmospheric emissions resulting from the production of asphalt mixtures in a laboratory environment — a subject for which data are still unavailable in the Brazilian context — the decision was made not to activate the exhaust system during measurements. This procedure represents an atypical condition in the laboratory's routine and was adopted exclusively for experimental purposes.

2.2. Indoor air quality monitoring

Measurements were conducted between April and May 2024 under two conditions: (i) with no laboratory activity; and (ii) during hot-mix asphalt production operations. In case (i), three reference measurements were carried out, regularly scheduled for Monday mornings from 8:00 a.m. to 10:00 a.m., after approximately 60 hours without any laboratory activity. In case (ii), six measurements were taken during hot-mix asphalt processing, on different weekdays, following the laboratory's operational schedule.

Following the routine laboratory practice, the asphalt mixtures were composed of crushed stone and stone dust as mineral aggregates and polymer-modified asphalt cement AC 60/85 as the binder. These materials were processed at high temperatures using a Solotest® closed-drum mixer, with mixing temperatures of 169 °C and processing durations ranging from 10 to 32 minutes. The emission monitoring period for the asphalt mixtures, regardless of the mixing duration, was set at 120 minutes for each of the six mixtures.

2.2.1. Air quality indicators

Atmospheric emissions generated during asphalt mixing were monitored using multiparameter analyzers, in accordance with the protocols established by NBR 17.037 (ABNT, 2023). The quantification of Total Suspended Particulate (TSP) was carried out using two AirCheck XR-5000 sampling pumps, operating at a flow rate of 3 L/min for 2 hours, totaling a sampled volume of 360 L per pump. Particle collection (TSP) was performed on PVC and cellulose acetate filter membranes, both 37 mm in diameter with a pore size of 5 µm.

The Temtop M2000 Elitech® device, equipped with a laser sensor, was used for real-time monitoring of inhalable particulate matter (PM₁₀) and fine particulate matter (PM_{2.5}), with a recording frequency of 1 min, resulting in approximately 120 readings during the sampling campaign. The device was positioned 2 m from the emission source.

The evaluation of additional parameters employed a CO₂ 77 AKSO® portable analyzer equipped with a non-dispersive infrared (NDIR) sensor for CO₂ measurement, as well as sensors for air temperature and relative humidity. In the gravimetric analysis of TSP, the PVC membranes were pre-dried for 24 hours and weighed using a Shimadzu AUW220D analytical balance. After sampling, the drying and weighing procedure was repeated to calculate the particulate concentration (µg/m³), based on the difference in dry mass and the volume of air processed. The regulatory limits for the evaluation of the pollutant levels monitored in this study are presented in Table 1.

Table 1: Summary table of recommended limits for indoor air pollutants

Temperature (°C)	Relative Humidity (%)	CO ₂ (ppm)	TSP (µg/m ³)	PM ₁₀ (µg/m ³)	PM _{2.5} (µg/m ³)	BaP (ng/m ³)
21 – 26 ^(a)	35-65 ^(a)	1150 ^{(a)*}	80 ^{(c)**}	75 ^(e)	37.5 ^(e)	1.2 ^(h)
		1000 ^(b)		50 ^(a)	25 ^(a)	1.0 ^(f)
				45 ^(d)	15 ^(d)	0.8 ^(g)

^(a)ABNT (2023); ^(b)UBA (2008); ^(c)ANVISA (Brasil, 2003); ^(d)WHO (2021); ^(e)EPD (2025); ^(f)European Union (2004); ^(g)UBA (2020); ^(h)Hong Kong (2019). *NBR 17037/2023 establishes that the internal level should be: external CO₂ + 700 ppm. The external level in this study = 450 ppm. **Since NBR 17037/2023 does not include TSP, the previous ANVISA (Brasil, 2003) limit was used as a reference.

2.2.2. Determination of metallic and organic micropollutants

Hot acid digestion of cellulose acetate filters was used to determine metal concentrations in TSP. The filters were placed in Teflon tubes, to which a mixture of HCl/HNO₃ (3:1) and HF (48%) was added until complete immersion. The containers were heated at 200-220 °C for 4 hours to ensure total digestion of the solids. After cooling, the extracts were diluted with ultrapure water (0.1 µS/cm) and analyzed using an atomic absorption spectrophotometer (iCE 3000®, Thermo Scientific), with specific calibration curves for each metal used for quantification.

The quantification of benzo(a)pyrene (BaP) adsorbed onto PVC filters was carried out by High-Performance Liquid Chromatography (HPLC). Extraction was performed in a Soxhlet system for 10 hours using an acetone/hexane solution (1:1, v/v). The filtered extracts were analyzed using a Varian ProStar® chromatograph with a Diode Array Detector (DAD), equipped with a Hypersil Green PAH column, operating at 225 nm. Benzo(a)pyrene (BaP) was used as a toxicological risk marker due to its carcinogenic potential (Stojić et al., 2022).

3. RESULTS AND DISCUSSION

3.1. Air quality indicators

According to Brazilian regulations (NBR 17.037/2023), indoor environments should operate in temperatures between 21 and 26 °C and relative humidity levels between 35 and 65% (ABNT, 2023). Figure 3 presents the recorded data on temperature and relative humidity and displays the CO₂ concentration levels monitored in the laboratory during asphalt mixture preparation and in the absence of laboratory activities.

Average temperatures remained stable under both laboratory operational conditions (Figure 3a). In contrast, relative humidity varied more during operation (up to 29%) than in idle conditions (6%). Still, values mostly remained within the limits established by the Brazilian standard NBR 17.037 (ABNT, 2023), except during samples 5 and 6, which were collected during operation — likely due to increased operation of the air conditioning system, which reduces humidity. These same samples also recorded the lowest temperatures, further supporting this hypothesis.

The laboratory's construction system presents limitations in terms of thermal comfort, especially considering its location in bioclimatic zone 6A (hot and humid climate), as defined by the Brazilian standard NBR 15220-3 (ABNT, 2024). The building has a single west-facing façade, which contributes to afternoon heat gain and prevents cross-ventilation by blocking prevailing winds from the east and southeast.

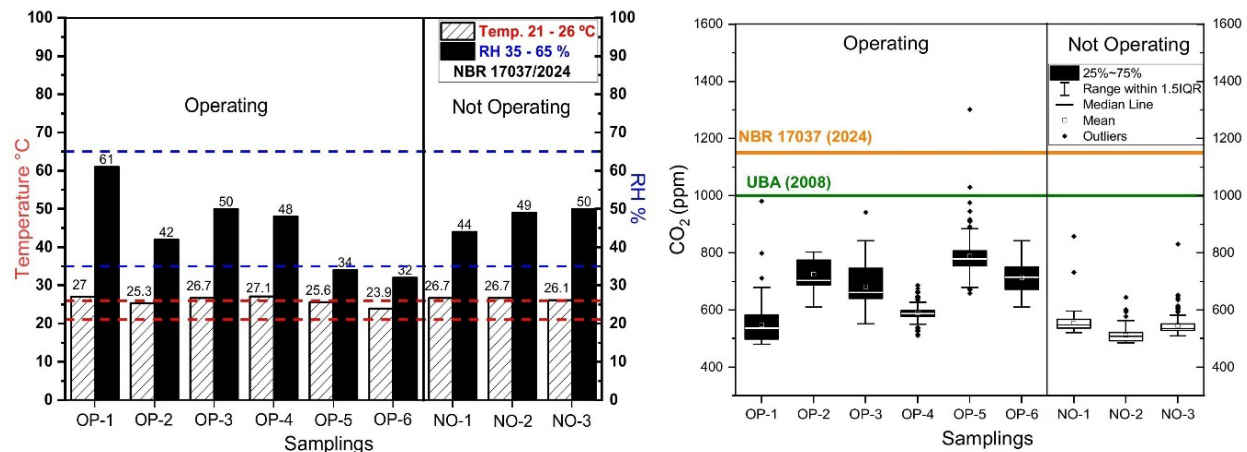


Figure 3. Temperature, relative humidity, and CO₂ in the asphalt mixing laboratory environment.

The ceramic block masonry walls with cement mortar finish and the ribbed reinforced concrete slab result in high thermal inertia, which is unfavorable for the local climate. In addition, the area of natural ventilation provided by the windows is limited, and there are no shading elements or passive strategies for heat mitigation, such as *brise-soleils* or perforated blocks (*cobogós*), compromising the building's bioclimatic performance.

Furthermore, the use of air conditioning systems without proper air renewal contributes to the deterioration of indoor environmental quality. This is because such systems continuously recirculate indoor air without introducing fresh outdoor air, promoting the accumulation of pollutants.

CO₂ concentrations (Figure 3b) ranged from 547.5 ppm (sample 1) to 788.2 ppm (sample 5), with a peak of 1,105 ppm in the latter, attributed to high occupancy (11 people, compared to an average of 4). In the absence of activities, CO₂ levels ranged from 511.39 ppm to 553.88 ppm, significantly lower. CO₂ emissions in indoor environments such as asphalt mixture laboratories typically originate from two main sources: emissions from thermal processes (e.g., combustion of fuels such as LPG and diesel) and biological emissions, primarily associated with human respiration. During the OP-1 and OP-4 sampling campaigns, low occupancy and no use of the LPG-fueled countertop stove were recorded, resulting in reduced CO₂ concentrations. During these periods, gas levels remained close to those observed under inactive laboratory conditions. In the other samplings — particularly in OP-5 — greater circulation of people and the use of the stove to heat asphalt binders likely contributed to higher localized CO₂ levels. Except for the peak value, all measurements remained within the limits established by the Brazilian standard NBR 17.037 (ABNT, 2023) and the German Environmental Agency (UBA, 2008). The values observed are comparable to those reported by Abdullah et al. (2016), who recorded 889.67 ppm for mixtures processed at 165 °C and between 533.01 and 790.67 ppm for mixing at 145 °C.

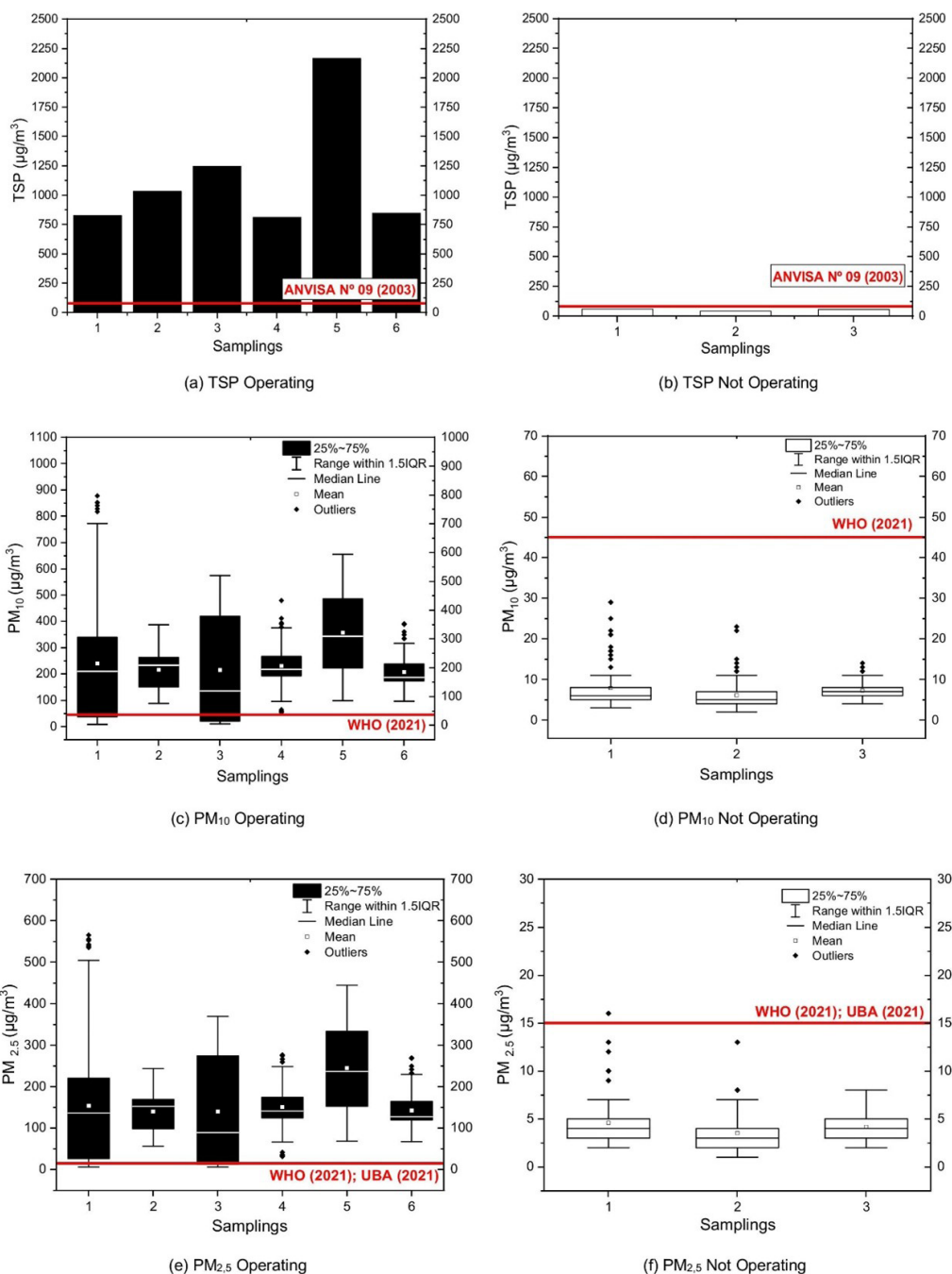
The concentrations of particulate matter analyzed during the laboratory study are presented in Table 2.

The average concentrations of particulate matter (TSP, PM₁₀, PM_{2.5}) were higher during the asphalt material processing period, while the recorded values decreased significantly in the absence of laboratory activities. Figure 4 provides a detailed presentation of particulate matter concentrations during the monitoring period.

Table 2: Average concentrations of particulate matter in the laboratory environment

Pollutant	Mixture	N	$\bar{x}$	σ	CV (%)	Maximum	Minimum
TSP ($\mu\text{g}/\text{m}^3$)	Not Operating	3	51.7	8.8	17.02	57.9	41.7
	Operating	6	1153.2	522.6	45.32	2163.9	810.2
PM ₁₀ ($\mu\text{g}/\text{m}^3$)	Not Operating	3	7.1	0.9	12.68	7.9	6.1
	Operating	6	244.0	56.5	23.16	356.9	207.0
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	Not Operating	3	4.1	0.5	12.20	4.6	3.5
	Operating	6	161.5	40.8	25.26	244.0	139.5

N: number of samples; $\bar{x}$: arithmetic mean; σ : standard deviation; CV: coefficient of variation.

**Figure 4.** Concentrations of particulate matter in the laboratory environment.

TSP concentrations ranged from 810.2 $\mu\text{g}/\text{m}^3$ (sample 4) to 2,163.9 $\mu\text{g}/\text{m}^3$ (sample 5). In sample 4, the asphalt processing time was 10 minutes, while in sample 5, the mixing duration was longer, reaching 34 minutes. This difference in operational conditions had a direct influence on the concentrations of particulate matter and other pollutants analyzed, which can be observed in the subsequent results throughout the study.

In a study conducted by Kitto et al. (1997), significantly elevated TSP concentrations were identified, ranging from 39,330 $\mu\text{g}/\text{m}^3$ to 45,620 $\mu\text{g}/\text{m}^3$, when heating asphalt to 200 °C. In that case, fume sampling was conducted directly at the furnace outlet, which explains the high levels observed.

PM_{10} concentrations showed a wide range of variation, particularly in sample 1 (12 minutes of mixing), which recorded values between 8 $\mu\text{g}/\text{m}^3$ and 877 $\mu\text{g}/\text{m}^3$, with an average of 239.29 $\mu\text{g}/\text{m}^3$, indicating the presence of peaks (outliers). The lowest range was observed in sample 6 (11 minutes of mixing), with values between 96 $\mu\text{g}/\text{m}^3$ and 391 $\mu\text{g}/\text{m}^3$ and an average of 207.05 $\mu\text{g}/\text{m}^3$, although still with measurements above the upper limit. These outliers are attributed to specific events such as the dumping of aggregates into the mixer and the cleaning of sieves using compressed air, both of which promote particle resuspension. Overall, PM_{10} concentrations exceeded the limits established by EPD (2025) at 75 $\mu\text{g}/\text{m}^3$, ABNT (2023) at 50 $\mu\text{g}/\text{m}^3$, and the WHO (2021), which adopts the most stringent limit of 45 $\mu\text{g}/\text{m}^3$.

Data on $\text{PM}_{2.5}$ concentrations show values ranging from 6 $\mu\text{g}/\text{m}^3$ to 565 $\mu\text{g}/\text{m}^3$, with an average of 153.23 $\mu\text{g}/\text{m}^3$ in sample 1, while in sample 6 the range was from 67 $\mu\text{g}/\text{m}^3$ to 269 $\mu\text{g}/\text{m}^3$, with an average concentration of 142.26 $\mu\text{g}/\text{m}^3$. Thus, the $\text{PM}_{2.5}$ values observed during asphalt mixing exceeded the exposure limits established by EPD (2025) at 37.5 $\mu\text{g}/\text{m}^3$, ABNT (2023) at 25 $\mu\text{g}/\text{m}^3$, UBA (2021) at 15 $\mu\text{g}/\text{m}^3$, and WHO (2021) also at 15 $\mu\text{g}/\text{m}^3$. In a similar study, Lin, Hung and Leng (2016) evaluated $\text{PM}_{2.5}$ emissions during laboratory-scale asphalt mixture processing. The authors found that, at 175 °C, average $\text{PM}_{2.5}$ concentrations ranged between 55.5 $\mu\text{g}/\text{m}^3$ and 115.1 $\mu\text{g}/\text{m}^3$.

The elevated concentrations of particulate matter in the laboratory environment may pose a significant threat to the respiratory system, as they can cause toxicity depending on the substances contained in their structure and the pollutants adsorbed on their surfaces (Ugranli et al., 2015). Inhalable particles such as $\text{PM}_{2.5}$ and PM_{10} are associated with serious health effects, including pulmonary diseases, asthma, and other respiratory issues. $\text{PM}_{2.5}$ particles, in particular, represent a greater health risk because they can bypass the upper airways and become lodged in the lungs (Gomes, 2002).

3.2. Metallic and organic micropollutants

With regard to the metallic and organic micropollutants present in the total particulate matter collected from the laboratory atmosphere, Table 3 presents the concentrations of metals and the PAH benzo(a)pyrene during the indoor air quality monitoring.

The analysis of metals present in the total suspended particulates collected during asphalt processing revealed a predominance of calcium (Ca), magnesium (Mg), and zinc (Zn), with higher concentrations observed in Samples 4 and 5, especially for Mg and Zn in Sample 5. The presence of these elements is characteristic of mineral-based materials, such as crushed stone (Gomes Neto et al., 2014; Achternbosch et al., 2005), which are widely used in asphalt mixtures. Nickel (Ni) and vanadium (V) were not detected in any of the samples collected. The assessment of these elements in particulate matter is analytically relevant, given their recognized toxic potential and associated adverse effects on occupational health, including bronchitis, chronic coughing, kidney impairment, and increased risk of lung and nasal cavity cancers (Lorenzoni, 2019; CETESB, 2022).

Table 3: Average concentrations of metallic and organic micropollutants present in TSP

	Ca	Mg	Zn	Pb	Ni	V	BaP
Coleta	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	($\mu\text{g}/\text{m}^3$)	(ng/m^3)
OP-1	76.4	26.8	1.5	ND	ND	ND	ND
OP-2	96.1	45.9	2.6	ND	ND	ND	4.8
OP-3	93.5	61.0	3.9	ND	ND	ND	6.4
OP-4	98.8	35.5	3.3	ND	ND	ND	ND
OP-5	173.8	124.2	9.4	ND	ND	ND	6.6
OP-6	96.2	88.2	2.1	ND	ND	ND	5.5
NOP-1	18.4	5.2	ND	ND	ND	ND	ND

OP: operating; NOP: not operating; ND: not detected.

PAH concentrations in the laboratory environment ranged from $4.8 \text{ ng}/\text{m}^3$ to $6.4 \text{ ng}/\text{m}^3$. A study conducted by Xiu et al. (2020) analyzed PAH emissions from asphalt mixtures using portable chambers placed over freshly laid asphalt. Those authors reported an average BaP concentration of $2.1 \text{ ng}/\text{m}^3$, which is lower (about half to one-third) than the values found in the present study. The European Union has established a standard limit for benzo(a)pyrene of $1 \text{ ng}/\text{m}^3$ (European Union, 2004), while the German Federal Environment Agency suggests a guideline value of $0.8 \text{ ng}/\text{m}^3$ for indoor environments (UBA, 2020). The World Health Organization reports that a BaP concentration of $1.2 \text{ ng}/\text{m}^3$, under long-term exposure, may lead to an excess cancer risk on the order of 1 in 10,000 (WHO, 2010).

In the context studied, the results indicate that asphalt material synthesis in a laboratory has produced atmospheric pollutant concentrations exceeding national and international recommended limits, highlighting the need for integrated environmental control measures and individual protective strategies in these settings. Respiratory protection for occupants becomes critical, particularly during phases involving binder heating, hot-mix asphalt processing, aging, and specimen molding, all of which release significant amounts of organic compounds in both gaseous and particulate phases.

Therefore, the use of respirators with combination cartridges (P100 filter coupled with activated carbon), as recommended by NIOSH (2023), is required to provide effective protection against both particulates and organic vapors.

In addition, PAHs can be absorbed through the skin, requiring the use of appropriate dermal protective equipment. During the handling of heated asphalt binders and mixtures, the use of Class 3 chemical-resistant gloves, in compliance with EN 374-1 standard (ISO, 2016), is essential. It is also recommended to wear full-seal safety goggles or face shields, especially during tasks with risk of splashes or projections, such as pouring hot asphalt binder.

From a built environment engineering perspective, enclosing the asphalt mixing area in a dedicated room with restricted access and an independent ventilation system is a critical measure to limit pollutant dispersion within the broader laboratory space. The facility is already equipped with a local exhaust system over the asphalt mixer, with ducts that direct fumes directly outside the building. However, ideally, this system should be installed together with the mixer in an isolated area designated exclusively for asphalt processing (hot room).

Finally, considering the variability in user profiles and the need to reduce cumulative exposure, it is advisable to establish organized operational routines, including prior scheduling of space usage and limiting the number of individuals present simultaneously in the hot area. Implementing rotational schedules helps minimize individual exposure time, promoting a safer working environment aligned with good laboratory practices.

4. CONCLUSION

The present study demonstrated that the production of asphalt mixtures in a laboratory environment results in the significant emission of atmospheric pollutants, including inhalable particles (PM_{10} and $PM_{2.5}$), total suspended particulate (TSP), metals (Ca, Mg, and Zn), and toxic organic compounds such as benzo(a)pyrene. The average concentrations of these contaminants exceeded the limits established by national and international guidelines.

The substantial presence of fine particulate matter and PAHs in the indoor laboratory air underscores the potential health risks to users' respiratory and systemic health, potentially contributing to the development of chronic diseases such as asthma, bronchitis, cardiovascular disorders, and even cancer.

The detailed characterization of emissions makes a new contribution to addressing gaps in the national literature regarding air quality in infrastructure laboratories. Thus, the findings not only reinforce the urgency of implementing engineering control measures (such as compartmentalization and localized exhaust systems), but also highlight the need for continuous use of appropriate Personal Protective Equipment (PPE) and restructuring of laboratory routines. Limiting the number of occupants, scheduling activities, and regularly monitoring air quality are recommended strategies to mitigate the identified risks.

It is recommended that emissions generated during asphalt mixture production be monitored both with the exhaust system turned off and activated, in order to evaluate the operational efficiency of this environmental control system.

For future investigations, it is advisable to conduct indoor temperature measurements during both morning and afternoon periods, exploring possible thermal variations due to direct solar radiation on the west-facing laboratory façade. Additionally, internal noise levels during laboratory activities should be assessed to verify whether sound levels remain within acceptable limits for occupational environments.

AUTHORS' CONTRIBUTIONS

MLS: Investigation, Methodology, Data Curation, Formal Analysis, Visualization, Writing — original draft, Writing — review and editing; MFPC: Investigation, Methodology, Writing — original draft; CJTN: Data Curation, Visualization; RSA: Project Administration, Conceptualization, Methodology, Supervision, Resources, Writing — review and editing, Validation; LSF: Supervision, Writing — review and editing, Validation; ISB: Resources, Writing — review and editing, Validation; LFALB: Project Administration, Funding Acquisition, Resources, Supervision, Writing — review and editing, Validation.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

This work was prepared with the assistance of Generative Artificial Intelligence (GenAI) ChatGPT, with the aim of supporting the translation of the text. The entire process of using this tool was supervised, reviewed, and, when necessary, edited by the authors.

DATA AVAILABILITY STATEMENT

All data generated or analyzed are included in this article and the supplementary information files.

ACKNOWLEDGEMENTS

This study was conducted with funding from the National Council for Scientific and Technological Development (CNPq) through Project 407235/2022-1 - Development of Innovative and Sustainable Products for Infrastructure and from the Program for Human Resource Training in Petroleum and Natural Gas Engineering and Sciences - PRH-31.1/ANP/FINEP, process: 2024/12090-9. Additional acknowledgment is extended to the Ceara Foundation for Scientific and Technological Development Support (FUNCAP) for supporting the research.

REFERENCES

- Abdullah, M.E.; M.R. Hainin; N.I.M. Yusoff et al. (2016) Laboratory evaluation on the characteristics and pollutant emissions of nanoclay and chemical warm mix asphalt modified binders. *Construction & Building Materials*, v. 113, p. 488-97. DOI: 10.1016/j.conbuildmat.2016.03.068.
- ABNT (2023) *NBR 17037: Qualidade do Ar Interior em Ambientes Não Residenciais Climatizados Artificialmente*. Rio de Janeiro: ABNT.
- ABNT (2024) *NBR 15220-3: Desempenho Térmico de Edificações – Parte 3: Zoneamento Bioclimático por Desempenho*. Rio de Janeiro: ABNT.
- Achternbosch, M.; K. Bräutigam; N. Hartlieb et al. (2005) Impact of the use of waste on trace element concentrations in cement and concrete. *Waste Management & Research*, v. 23, n. 4, p. 328-37. DOI: 10.1177/0734242X05056075. PMID:16200983.
- Alcântara, A.P.M.P.; J.P. Ribeiro; I.G.R. Segundo et al. (2023) Diagnóstico de emissões de poluentes atmosféricos na produção de misturas asfálticas. *Transportes*, v. 31, n. 3, p. 1-12. DOI: 10.58922/transportes.v31i3.2887.
- Alcântara, A.P.M.P.; J.P. Ribeiro; L.M. Barbosa et al. (2019) Avaliação da emissão de material particulado e dióxido de nitrogênio na usinagem de misturas asfálticas. In *Anais do XXXIII Congresso de Pesquisa e Ensino em Transportes* (Balneário Camboriú, SC). Balneário Camboriú: ANPET, p. 1841-1852.
- Bernucci, L.B.; L.M.G. Motta; J.A.P. Ceratti et al. (2022) *Pavimentação Asfáltica: Formação Básica para Engenheiros* (2a ed.). Rio de Janeiro: ABEDA.
- Branco, P.T.B.S.; S.I.V. Sousa; M.R. Dudzińska et al. (2024) A review of relevant parameters for assessing indoor air quality in educational facilities. *Environmental Research*, v. 261, p. 119713. DOI: 10.1016/j.envres.2024.119713. PMID:39094896.
- Brasil, Agência Nacional de Vigilância Sanitária (2003) *Resolução - RE nº 9: padrões referenciais de qualidade do ar interior, em ambientes climatizados artificialmente de uso público e coletivo*. Diário Oficial da República Federativa do Brasil.
- CETESB (2022) *FIT – Ficha de Informação Toxicológica: Níquel, Vanádio e seus Compostos*. São Paulo: Divisão de Toxicologia e Saúde Animal.
- EPD (2025) *Hong Kong Air Quality Objectives*. Environmental Protection Department, The Government of Hong Kong Special Administrative Region. Available at: <https://www.epd.gov.hk/epd/english/environmentinhk/air/air_quality_objectives/air_quality_objectives.html> (accessed 06/27/2025).
- European Union (2004) Directive 2004/107/EC of the European parliament and of the council of 15 December 2004 relating to Arsenic, Cadmium, Mercury, Nickel and Polycyclic Aromatic Hydrocarbons in Ambient Air. *Official Journal of the European Union*.
- Gaudefroy, V.; D.L. Presti; L. Porot et al. (2022) Organic compounds evaluation from fumes generated in laboratory by bio-recycled asphalt mixtures. *Journal of Testing and Evaluation*, v. 50, n. 2, p. 920-7. DOI: 10.1520/JTE20210201.
- Germin-Aizac, J.; A. Maitre; F. Balducci et al. (2023) Bitumen fumes and PAHs in asphalt road paving: emission characteristics, determinants of exposure and environmental impact. *Environmental Research*, v. 228, p. 115824. DOI: 10.1016/j.envres.2023.115824. PMID:37030408.
- Gomes Neto, D.P.; H. Conceição; V.A.C. Lisboa et al. (2014) Influence of granitic aggregates from northeast Brazil on the alkali-aggregate reaction. *Materials Research*, v. 17, p. 51-8. DOI: 10.1590/S1516-14392014005000045.
- Gomes, M.J.M. (2002) Ambiente e pulmão. *Jornal de Pneumologia*, v. 28, n. 5, p. 261-9. DOI: 10.1590/S0102-35862002000500004.
- Han, S.; J. Lee and C. Baek (2023) Evaluation of emission characteristics and microstructure of particulate matters from excavation and restoration work on asphalt concrete pavement. *Applied Sciences*, v. 13, n. 1, p. 323. DOI: 10.3390/app13010323.
- Hong Kong (2019) *A Guide on Indoor Air Quality Certification Scheme for Offices and Public Places*. Indoor Air Quality Management Group, The Government of the Hong Kong Special Administrative Region.
- ISO (2016) *EN ISO 374-1:2016 - Protective Gloves Against Dangerous Chemicals and Micro-Organisms – Part 1: Terminology and Performance Requirements for Chemical Risks*. Geneva: ISO.
- Jang, T.; Y. Kim; J. Won et al. (2018) The standards for recognition of occupational cancers related with polycyclic aromatic hydrocarbons (PAHs) in Korea. *Annals of Occupational and Environmental Medicine*, v. 30, n. 1, p. 13. DOI: 10.1186/s40557-018-0224-1. PMID:39541432.
- Kharat, D.S. (2022) Emissions from hot mix asphalt plants and their impact on ambient air quality. *Water, Air, and Soil Pollution*, v. 233, n. 11, p. 464. DOI: 10.1007/s11270-022-05950-w.
- Kitto, A.M.; M. Pirbazari; B.N. Badriyha et al. (1997) Emissions of volatile and semi-volatile organic compounds and particulate matter from hot asphalts. *Environmental Technology*, v. 18, n. 2, p. 121-38. DOI: 10.1080/09593331808616520.
- Li, J.; Y. Qin; X. Zhang et al. (2024) Emission characteristics, environmental impacts, and health risks of volatile organic compounds from asphalt materials: a state-of-the-art review. *Energy & Fuels*, v. 38, n. 6, p. 4787-802. DOI: 10.1021/acs.energyfuels.3c04438.

- Lin, S.; W. Hung and Z. Leng. (2016) Air pollutant emissions and acoustic performance of hot mix asphalts. *Construction & Building Materials*, v. 129, p. 1-10. DOI: 10.1016/j.conbuildmat.2016.11.013.
- Lorenzoni, W.C. (2019) *Estudo de Compostos Orgânicos Voláteis de Níquel e Vanádio em Cimento Asfáltico de Petróleo Virgem e Envelhecido*. Dissertação (mestrado). Programa de Pós-graduação em Química, Universidade Federal de Santa Maria. Santa Maria. Available at: <<http://repositorio.ufsm.br/handle/1/17196>> (accessed 05/14/2025).
- Lucas Jr., J.L.O.; L.F.A.L. Babadopulos and J.B. Soares (2019) Aggregate-binder adhesiveness assessment and investigation of the influence of morphological and physico-chemical properties of mineral aggregates. *Road Materials and Pavement Design*, v. 20, n. sup1, p. 579-94. DOI: 10.1080/14680629.2019.1588773.
- Mousavi, M.; J. Emrani; J.C. Teleha et al. (2024) Health risks of asphalt emission: State-of-the-art advances and research gaps. *Journal of Hazardous Materials*, v. 480, p. 136048. DOI: 10.1016/j.jhazmat.2024.136048. PMID:39405707.
- NIOSH (2023) *Guide to the Selection and Use of Particulate Respirators Certified Under 42 CFR 84*. Washington, D.C.: Department of Health and Human Services.
- Saleh, A.M.M.; F.H. Ashour and Y.M. Moustafa (2006) Assessment of the air quality in some Egyptian asphalt laboratories. *Current World Environment*, v. 1, n. 2, p. 117-24. DOI: 10.12944/CWE.1.2.04.
- Sandaka, G.; L.T. Gouveia and L.J. Senger (2018) Emissões do asfalto e seus efeitos na saúde humana. *Transportes*, v. 26, n. 2, p. 167-79. DOI: 10.14295/transportes.v26i2.1613.
- Stojić, A.; G. Jovanović; S. Stanišić et al. (2022) The PM_{2.5}-bound polycyclic aromatic hydrocarbon behavior in indoor and outdoor environments, part II: explainable prediction of benzo[a]pyrene levels. *Chemosphere*, v. 289, p. 133154. DOI: 10.1016/j.chemosphere.2021.133154. PMID:34871609.
- Suvarapu, L.N. and S. Baek (2017) Determination of heavy metals in the ambient atmosphere. *Toxicology and Industrial Health*, v. 33, n. 1, p. 79-96. DOI: 10.1177/0748233716654827. PMID:27340261.
- Tang, N.; K. Yang; Y. Alrefaei et al. (2020) Reduce VOCs and PM emissions of warm-mix asphalt using geopolymer additives. *Construction & Building Materials*, v. 244, p. 118338. DOI: 10.1016/j.conbuildmat.2020.118338.
- UBA, German Committee on Indoor Air Guide Values (2008) *Hygienic Guide Values for Carbon Dioxide*. Available at: <<https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values#indoor-air-guide-values>> (accessed 11/18/2024).
- UBA, German Committee on Indoor Air Guide Values (2020) *Risk-related Guide Values for Carcinogenic Substances in Indoor Air*. Available at: <<https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values#indoor-air-guide-values>> (accessed 11/18/2024).
- UBA, German Committee on Indoor Air Guide Values (2021) *Hygienic Guide Values for Particulate Matter in Indoor Air*. Available at: <<https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values#indoor-air-guide-value>> (accessed 11/18/2024).
- Ugranli, T.; M. Toprak; G. Gursoy et al. (2015) Indoor environmental quality in chemistry and chemical engineering laboratories at Izmir Institute of Technology. *Atmospheric Pollution Research*, v. 6, n. 1, p. 147-53. DOI: 10.5094/APR.2015.017.
- USEPA (2024) *Reference Guide for Indoor Air Quality in Schools*. Washington, D.C.: Indoor Environments Division. Available at: <<https://www.epa.gov/iaq-schools/reference-guide-indoor-air-quality-schools>> (accessed 10/13/2024).
- von Gunten, K.; K.O. Konhauser and D.S. Alessi (2020) Potential of asphalt concrete as a source of trace metals. *Environmental Geochemistry and Health*, v. 42, n. 2, p. 397-405. DOI: 10.1007/s10653-019-00370-y. PMID:31309375.
- Wang, M.; P. Li; T. Nian et al. (2021) An overview of studies on the hazards, component analysis and suppression of fumes in asphalt and asphalt mixtures. *Construction & Building Materials*, v. 289, p. 123185. DOI: 10.1016/j.conbuildmat.2021.123185.
- Wang, Y.; W. Wang and L. Wang (2022) Understanding the relationships between rheology and chemistry of asphalt binders: a review. *Construction & Building Materials*, v. 329, p. 127161. DOI: 10.1016/j.conbuildmat.2022.127161.
- WHO (2004) *Asphalt (Bitumen)*, Concise International Chemical Assessment Document, no. 59. Geneva: WHO.
- WHO (2010) *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Geneva: WHO.
- WHO (2021) *WHO Global Air Quality Guidelines: Particulate Matter (PM_{2.5} and PM₁₀), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Executive Summary*. Geneva: WHO.
- Xiu, M.; X. Wang; L. Morawska et al. (2020) Emissions of particulate matters, volatile organic compounds and polycyclic aromatic hydrocarbons from warm and hot asphalt mixes. *Journal of Cleaner Production*, v. 275, p. 123094. DOI: 10.1016/j.jclepro.2020.123094.
- Xu, Y.; C.H. Lindh; B.A. Jönsson et al. (2018) Occupational exposure to asphalt mixture during road paving is related to increased mitochondria DNA copy number: a cross-sectional study. *Environmental Health*, v. 17, n. 1, p. 29. DOI: 10.1186/s12940-018-0375-0. PMID:29587765.