Annals of Work Exposures and Health, 2021, Vol. 65, No. 4, 446–457
doi: 10.1093/annweh/wxaa129
Advance Access publication 15 February 2021
Original Article

The Chartered Society for Worker Health Protection
OXFORD

Original Article

Occupational Exposure during Asphalt Paving—Comparison of Hot and Warm Mix Asphalt in Field Experiments

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Submitted 10 February 2020; revised 17 November 2020; editorial decision 18 November 2020; revised version accepted 25 November 2020.

Abstract

Objectives: Several studies have demonstrated an increased risk of adverse health effects, including reduced lung function and lung cancer among asphalt pavers, which has been related to occupational exposure to contaminants during asphalt paving. Consequently, occupational exposure among asphalt pavers must be reduced. The aim of this study was to compare the impact of hot mix asphalt (HMA) and warm mix asphalt (WMA) paving on occupational exposure levels during road paving in field experiments. Asphalt temperatures when paving with WMA are usually lower than when paving with HMA due to differences in the asphalt's composition and method of application.
Methods: On 11 different road sections, one lane was paved with WMA and one with HMA during the same work shift under approximately identical weather conditions. The weather conditions and asphalt surface temperature were monitored during paving. Fifty-seven samples of fumes and vapor, organic and elemental carbon, amines, and respirable, thoracic, and inhalable particulate matter (PM) fractions were collected by stationary sampling. In addition, 30 samples of fumes and vapor were collected by personal sampling
Results: Compared to paving with HMA, paving with WMA significantly ($P < 0.05$; paired Student's *t*-test) reduced the geometric mean (GM) air concentration of asphalt vapor (0.04 versus 0.08 p.p.m.), organic carbon (OC; 0.09 versus 0.18 mg m^{-3}), and respirable PM (0.12 versus 0.22 mg m^{-3}). Additionally, the air concentration of OC correlated strongly with the respirable fraction of PM (Pearson's correlation coefficient 0.83).
Conclusions: Measured airborne concentrations of respirable PM, OC, and asphalt vapor were lower when paving with WMA than with HMA. Because exposure to airborne contaminants generated during asphalt paving is believed to be responsible for the adverse health effects observed among asphalt pavers, paving with WMA rather than HMA may have health benefits.

What's important about this paper?

Asphalt paving has been associated with adverse pulmonary outcomes, motivating reduction of occupational exposures. In a series of field-based experiments, we found paving with warm mix asphalt (WMA) resulted in reduced levels of airborne respirable particulate matter, organic carbon, and asphalt vapor compared to paving with hot mix asphalt, though no effect was observed in the breathing zone of screedmen. This is the first study to measure the impact of WMA in the field, and demonstrates that this approach may reduce occupational exposures to airborne contaminants during asphalt paving.

Keywords: asphalt fumes; asphalt pavingorganic carbon; respirable dust

Introduction

Adverse health effects among asphalt workers caused by occupational exposure during asphalt paving have been studied for several years. Some studies have shown that occupational exposure to contaminants released during asphalt paving can cause irritative symptoms in the eyes and upper airways (Raulf-Heimsoth *et al.*, 2007). Additionally, several studies have shown that asphalt pavers exhibit reduced lung function and increased mortality due to obstructive lung diseases (Burstyn *et al.*, 2003; Ulvestad *et al.*, 2007; Neghab *et al.*, 2015; Ulvestad *et al.*, 2017). An increased risk of lung and bladder cancer as well as heart diseases has also been reported (Boffetta *et al.*, 2003; Randem *et al.*, 2004; Burstyn *et al.*, 2005; Burstyn *et al.*, 2007; Olsson *et al.*, 2010; Mundt *et al.*, 2018). Consequently, there is a need to minimize exposure to airborne contaminants during paving.

Levels of airborne contaminants including respirable particulate matter (PM), total PM, polycyclic aromatic hydrocarbons (PAH), and oil mist and vapor have been measured during asphalt paving (Burstyn *et al.*, 2002; Heikkila et al., 2002; Elihn *et al.*, 2008; Cavallari *et al.*, 2012; Osborn *et al.*, 2013; Nilsson *et al.*, 2018). However, few studies have investigated airborne contaminants generated during paving with asphalt at different temperatures. Determinants such as work tasks, type of asphalt, asphalt-paving temperature, paving methods, and meteorological conditions have been suggested to have important effects on airborne contaminant exposure during asphalt paving (Brandt and de Groot, 1999; Burstyn *et al.*, 2000; Heikkila et al., 2002; Cavallari *et al.*, 2012). Additionally, laboratory experiments have shown that asphalt temperature and bitumen volatility are important determinants of exposure (Brandt and de Groot, 1999; Nilsson *et al.*, 2018; Mo *et al.*, 2019). It would therefore be desirable to know how the occupational exposure of asphalt pavers changes when asphalt is applied at lower temperatures outdoors.

When paving, the asphalt must be kept warm enough to maintain a viscosity that confers adequate workability and the production of a smooth and durable road surface after paving. The asphalt temperature is typically between 140 and 180°C depending on the type of asphalt being used. Asphalt applied in this temperature interval is often referred to as hot mix asphalt (HMA) (Rubio *et al.*, 2012). Conversely, warm mix asphalt (WMA) is usually 20–40°C cooler during paving.

There are two main methods of producing WMA: foaming and additive (Capitão *et al.*, 2012). When using the foaming method, water is sprayed into hot bitumen before it is mixed with sand and stone materials. This process creates micropores of steam in the bitumen, increasing its volume and thus reducing the viscosity of the finished asphalt. Alternatively, WMA can be produced by mixing bitumen with additives that coat and lubricate the aggregated particles, enabling paving at lower temperatures. These additives can be either organic compounds (e.g. emulsifiers) or other chemicals (e.g. surfactants). WMA essentially has the same composition as HMA, but the amount and type of additives in the bitumen may be varied to optimize viscosity (Rubio *et al.*, 2012).

The issue of occupational exposure among asphalt pavers has attracted attention in Norway, and it has been suggested that asphalt temperatures should be reduced to limit this exposure (Burstyn *et al.*, 2002; Ulvestad *et al.*, 2007). A study was therefore conducted to investigate whether replacing HMA with WMA could reduce asphalt pavers' occupational exposure to airborne contaminants without adversely affecting asphalt viscosity or road surface durability, which is of major societal importance in terms of both traffic safety and financial considerations. With regard to the latter issue, it should be noted that annual follow-up measurements conducted over a 5-year period indicated that roads laid using WMA exhibited comparable durability to those laid using HMA (Jørgensen, 2017).

The aim of this study was to investigate and compare occupational exposure to selected airborne contaminants during paving with HMA and WMA in real working environments. The study was designed to permit direct comparison of contaminants generated during paving with the two asphalt types on the same road sections (one lane for each asphalt type) on the same day, under similar weather conditions. The gravel and bitumen used in the asphalts was also kept as similar as possible. To the best of our knowledge, this is the first field study comparing occupational airborne exposure generated during paving with HMA and WMA outdoors.

Materials and methods

Study design

Eleven different road sections approximately 1 km in length at different locations in Norway were selected for paving by the Norwegian Public Roads Administration for these field experiments. The road sections were located close to production sites of asphalt manufacturers able to produce both WMA and HMA.

One lane of each road section was paved with WMA and the other with HMA. The field experiments were conducted at night when traffic densities were relatively low. Paving with WMA was done first. In each experiment, the left road lane was paved with WMA over approximately 3 h, after which the paving machines were returned to their starting point and the right road lane was paved with HMA, theoretically generating a total of 22 measurement series. This experimental design was chosen to ensure that the conditions during paving with HMA and WMA on each road section were as similar as possible. Road traffic was allowed to pass during paving.

Paving was not started if the wind speed was above 4 m s^{-1} or during heavy rain. Additionally, field experiments in progress were interrupted if the average wind rose above 4 m s^{-1} or heavy rainfall commenced. Observations from field experiments were excluded if the arithmetic mean (AM) wind speed during paving with WMA differed from that during paving with HMA by 1 m s^{-1} or more. Observations from one field experiment were excluded on this ground; the wind speed difference in this case was 7 m s^{-1}.

Sampling strategy

An adjustable sampling rig was attached to the asphalt-paving machines, allowing three stationary samplers to be mounted at the same height (180–200 cm above the asphalt) and in the same location in the breathing zone of the pavers. In each field experiment, the same paving machine was used for WMA and HMA. Air samples of fumes, vapors, organic carbon (OC), elemental carbon (EC), amines, and the respirable, thoracic, and inhalable PM fractions were collected during paving. PAH measurements were not performed because a previous Norwegian study using similar HMA found only low levels of PAH during paving (Burstyn *et al.*, 2002). The temperature of the asphalt surface was measured approximately 0.5 m behind the point of asphalt application every 10th minute during paving. Samples of fumes and vapor were also collected by personal sampling of the two screedmen, who worked close to the asphalt paver during each measurement series.

Wind speed, wind direction, and ambient air temperature were continuously monitored and logged during paving. These meteorological data were collected on the opposite side of the driver's seat, and on top of the roof of the asphalt-paving machine to minimize disturbance of the measurements. The orientation of the asphalt-paving machine was used as the reference direction when determining the wind direction.

Sampling methods

Asphalt fumes and vapor generated during paving were collected with a combined dust–vapor sampler consisting of a 37 mm total dust cassette (Millipore, Massachusetts, USA) fitted with a 2.0 µm pore size Pall Zefluor Teflon filter (Pall Industries, New York, USA) connected in series with an activated charcoal adsorbent tube (SKC part no. 226-09) (SKC, Dorset, UK). The sampler was operated at an airflow rate of 2 l min^{-1} using an SKC AirChek 224-PCXR8 air sampling pump (SKC, Dorset, UK). Six of the 57 samples collected with the sampling rig were excluded due to pump failure.

Fifty-seven samples of PM in the respirable, thoracic, and inhalable aerosol fractions were collected simultaneously with three-stage RespiCon impactors (Helmut Hund GmbH, Wetzlar, Germany) equipped with Pall Zefluor Teflon filters having a pore size of 2.0 µm (Pall Industries, New York, USA). The RespiCon sampler was operated at an airflow rate of 3.11 l min^{-1} using an SKC AirChek 224-PCXR8 air sampling pump.

Fifty-seven samples of OC and EC were collected with 25 mm Millipore total dust cassettes (Millipore, Massachusetts, USA) equipped with 25 mm Whatman Q-MA quartz filters (VWR, Radnor, Pennsylvania, USA) and a stainless steel filter support (JS Holdings, Stevenage, UK). The sampler was operated at an airflow rate of 2 l min^{-1} with an in-house built PS103 air sampling pump (NIOH, Oslo, Norway).

Fifty-seven samples of amines were collected with XAD-2 adsorbent tubes impregnated with 1-naphthylisothiocyanate (SKC part no. 226-30-18) (SKC, Dorset, UK). Amines were collected with an in-house built PS103 air sampling pump fitted with a low-flow adapter (SKC part no. 224-26-01) (SKC, Dorset, UK) operated at an airflow rate of 0.1 l min^{-1}.

Air sampling flow rates were measured before and after each sampling event using a DryCal DC-Lite flowmeter (Bios International Corp., New York, USA).

Weather conditions were determined using a MetPak II weather station (Gill Instruments, New Milton, UK), which recorded the wind speed (0–60 m s^{-1}, with a resolution of 0.01 m s^{-1}), wind direction (0–360°, with a resolution of 1°) and air temperature (−50–100°C, with a resolution of 0.1°C). According to the manufacturer, the measurement accuracy for the wind speed, wind direction, and air temperature are ±2%, ±3° at 12 m s^{-1} wind speed, and ±0.1°C, respectively.

Asphalt surface temperatures were measured manually with a Fluke 561 IR thermometer (Fluke Calibration, Washington, USA), which has an accuracy of ±1°C.

Analyses

Concentrations of asphalt fumes and PM were determined gravimetrically, after conditioning the filters for 48 h, in a climate-controlled weighing room (20 ± 1°C and RH% 40 ± 2%) by weighing the filters before and after sampling using a Sartorius MC 5 microbalance (Sartorius AG, Göttingen, Germany). The air concentration limit of detection (cLOD) for the gravimetric measurement of asphalt fumes was 0.41 mg m^{-3}. For PM samples collected with the three-stage RespiCon impactors, the LOD for the thoracic and inhalable fractions was based on the merged masses from two or three stages, respectively. Consequently, the LODs for these fractions were higher than that for the respirable fraction, for which the LOD was based on one stage only.

The gravimetric LOD for PM collected with the RespiCon impactors was determined by weighing a set of six filters mounted in different samplers that were transported (in the field) and stored in the same manner as the filters used for sampling. During the field experiments, two different batches of Teflon filters were used in the RespiCon impactors. The two batches of filters yielded different LODs because the variance in the weights of the second batch exceeded that for the first. The second batch of filters was also more fragile and thus more severely affected by the process of mounting and disassembling the filter holders in the RespiCon impactor. The cLODs for the gravimetric determinations of PM levels were thus 0.033/0.14, 0.048/0.19,, and 0.058/0.24 mg m^{-3} for the respirable, thoracic, and inhalable fractions, respectively, when using filter batches 1 and 2, respectively. Due to the high cLODs achieved with the second batch of filters (which were used in five field experiments), the PM contents of most of the 30 respirable fraction samples acquired using these filters were below the cLOD. These results were not included in the statistical analysis.

After weighing, each filter used to collect asphalt fumes was transferred to a 4 ml sample vial and extracted with 3.0 ml of carbon disulfide (CS_2). The resulting solution was analyzed with an Agilent 6890 (Agilent, Santa Clara, CA, USA) gas chromatograph (GC) equipped with an Agilent HP-5 GC column (30 m × 0.32 mm × 1.00 µm) and a flame ionization detector (GC-FID). Asphalt vapor was extracted from the charcoal tubes with 3.0 ml of CS_2 and subsequently analyzed by GC-FID. The LOD of each component was 0.00005 p.p.m., quantified against *n*-dodecane ($C_{12}H_{26}$).

OC and EC were determined with a thermo-optical instrument (Sunset Laboratory Inc., Tigard, OR, USA) according to NIOSH Method 5040. The cLODs, based on a sampling time of 180 minutes at 2 l min^{-1}, were 0.0011 mg m^{-3} for EC and 0.011 mg m^{-3} for OC, determined using *n*-hexacosane ($C_{26}H_{54}$) as a reference compound.

Amines were extracted with 1.5 ml acetonitrile and subsequently analyzed using a Waters CapLC instrument with a photodiode array (PDA) ultraviolet (UV) detector operating at 254 and 280 nm (Waters, Milford, MA, USA). The CapLC-PDA instrument was used with a 200 × 1.0 mm Grom-sil 80 ODS-7 pH LC column with 4 µm particles (Grace, Worms, Germany), an injection volume of 1 µl, and an isocratic mobile phase consisting of acetonitrile and water (50:50, v/v). The sample extracts were quantified against known amounts of volatile amines. The calibration standards were matrix-matched by adding 1.5 ml of a calibration standard solution to adsorbent from a blank adsorbent tube. The LODs of the volatile amines methylamine, ethylamine, *n*-propylamine, *n*-butylamine, dimethylamine, diethylamine, di-*n*-propylamine, ethylenediamine, and 1,3-diaminopropane were 0.002, 0.002, 0.002, 0.002, 0.004, 0.003, 0.002, 0.003, and 0.001 p.p.m., respectively.

Statistics

Exposure data that were non-normally distributed according to the Shapiro–Wilk test (alpha set to 0.05) were normalized by ln-transformation prior to analysis. The geometric mean (GM), geometric standard deviation (GSD), min, and max were used to describe non-normally distributed data. For normally distributed data, the arithmetic mean (AM), min, and max were used. No outliers were identified when the data were assessed using Grubbs' test. In one field experiment, paving with HMA could not be performed on the same day as with WMA due to heavy rain. In this experiment, data for another road section paved on the day before, at the same location and using HMA from the same supplier, were used as a reference.

Because the study design was intended to generate paired measurements of exposure during paving with WMA and HMA, two-sided paired Student's *t*-tests were performed on the ln-transformed data to assess the significance of observed differences in the air concentrations of contaminants when paving with WMA and HMA. Differences were considered statistically significant if $P < 0.05$. Concentrations below the LOD were substituted with LOD/√2. The variance between and within sampling positions was calculated using variance component analysis in SPSS.

Pearson´s correlation coefficient was calculated to measure the strength of observed associations. Least squares regression analyses were performed to assess the associations between the air contaminant concentrations measured during paving with HMA and WMA.

A linear mixed model was generated to assess differences in air contaminant concentrations with independent adjustments for air temperature, wind speed, wind direction, and the air concentration of EC. In the mixed model, the ln-transformed individual measurements were set as dependent variables and the sampling positions as the random intercept. The asphalt type, air temperature, wind speed, wind direction, and EC concentration were modeled as fixed effects. The inclusion of a random intercept gave rise to a compound symmetry variance structure.

$$\text{Dependent variable} = \beta o + \beta f + \beta r + ei$$

- Dependent variables: OC, asphalt vapor, respirable PM, thoracic PM, inhalable PM. In the analysis, dependent variables were log-transformed due to their skewed distribution.
- βo: Intercept, a constant that is the same for all participants.
- β*f*: Fixed variable; asphalt type, air temperature, wind speed, wind direction, EC. These were tested individually and in combination.
- β*r*: Random variables; sampling position in the rig. Assumed normally distributed with zero mean and variance · (between-position variance).
- ei: Residual error. Assumed normally distributed with zero mean and variance · (within-position variance).

βr is independent of ei

The statistical analyses were performed using IBM SPSS (25.0) (SPSS Inc., IL, USA) and the Real Statistics Resource Pack software (Release 5.4) (©2013–2018, Charles Zaiontz) for Microsoft Excel (2013) (Microsoft, WA, USA).

Results

Meteorological data and asphalt temperature measurements

The meteorological conditions and asphalt surface temperatures observed during paving are summarized in Table 1. The AM ambient air temperature varied between 14.2 and 20.0°C. The AM air temperature during paving with WMA was higher than during paving with HMA, as expected given the experimental setup: paving with HMA was performed later at night than paving with WMA. The AM wind speed varied between 0.86 and 1.05 m s^{-1} and was similar between HMA and WMA. The wind direction varied between 136° and 185° relative to the orientation of the paving machine.

The AM temperature of the newly paved asphalt surfaces is shown in Table 1. The asphalt surface temperatures when paving with HMA and WMA varied in the ranges 146–161°C and 112–135°C, respectively. The mean difference in asphalt surface temperature between HMA and WMA in the field experiments was 30°C.

Stationary sampling

The GM asphalt vapor concentration was significantly lower when paving with WMA (GM 0.04 p.p.m., GSD 5.57) than with HMA (GM 0.08 p.p.m., GSD 4.03) according to a paired *t*-test using the ln-transformed data (Table 2). Additionally, the variance within sampling positions (same position in the sampling rig in different experiments) was greater than that between sampling positions (between positions in the rig in the same experiment). Only nine measurements of asphalt fumes were above the LOD, so the asphalt fume results are not tabulated.

Table 1. Meteorological data and asphalt temperatures measured during field experiments involving paving with hot mix asphalt (HMA) and warm mix asphalt (WMA).

Type of asphalt	N[a]	Asphalt temperature (°C)		Wind speed (m s^{-1})		Wind direction (°)	Air temperature (°C)	
		AM[b]	Min–max	AM	Min–max	AM	AM	Min–max
WMA	10	126	112–135	0.96	0.55–1.73	163	18.8	15.6–24.9
HMA	9	155	146–164	0.94	0.61–1.50	150	16.7	12.1–20.4
WMA (additive)	5	128	115–135	1.05	0.55–1.73	140	20.0	15.6–24.9
HMA[c]	5	155	146–161	0.98	0.61–1.21	136	18.6	17.1–20.4
WMA (foam)	5	124	112–129	0.86	0.58–1.39	185	17.5	16.1–19.5
HMA[d]	4	156	150–164	0.88	0.64–1.50	168	14.2	12.1–19.1

Separate results are also shown for foam WMA and additive WMA. In one experiment, paving with HMA was not performed.
[a]Number of field experiments.
[b]Arithmetic mean.
[c]Corresponding road sections paved with additive WMA.
[d]Corresponding road sections paved with foam WMA.

The GM of the measured respirable PM concentrations when paving with WMA (GM 0.12 mg m^{-3}, GSD 2.83) was significantly lower than when paving with HMA (GM 0.22 mg m^{-3}, GSD 2.43). Additionally, the GM thoracic and inhalable PM concentrations were non-significantly lower when paving with WMA than with HMA (Table 2). As with the asphalt vapor concentrations, the variance in PM concentrations within sampling positions exceeded that between sampling positions.

Ethylamine was detected in only 12 of the 57 air samples. These 12 samples originated from four field experiments. The ethylamine concentrations in these 12 samples varied between 0.003 and 0.017 p.p.m. Methylamine was detected in 12 samples from three experiments, at concentrations of 0.003–0.004 p.p.m.

The GM OC air concentration was statistically significantly lower when paving with WMA (0.087 mg m^{-3}) than with HMA (0.176 mg m^{-3}) (Table 2). The variance in OC concentrations within sampling positions was similar to that between sampling positions. The GM EC air concentrations were 0.002 mg m^{-3} (GSD 1.52, min–max; 0.001–0.003 mg m^{-3}) when paving with HMA and 0.003 mg m^{-3} (GSD 1.37, min–max; 0.002–0.004 mg m^{-3}) when paving with WMA.

Pearson's correlation coefficient was calculated to evaluate the correlations between OC and EC (0.31; 95% confidence interval (CI) 0.05–0.53), asphalt vapor and respirable PM (0.40; 95% CI 0.15–0.60), and OC and respirable PM (0.83; 95% CI 0.65–0.92). Scatterplots showing the regression lines for the relationships between these variables are presented in Fig. 1.

Linear mixed model

The impact of air temperature, wind speed, wind direction, and the air concentration of EC on air contaminant concentrations during paving with WMA or HMA are shown in Supplementart File 1. Adjusting for air temperature had a significant impact in the linear mixed model, so the air temperature was used to adjust the differences in the mean air concentrations of OC, asphalt vapor, and PM (after ln-transformation) measured during paving with HMA and WMA (Table 3 and Supplementary material). After adjusting for air temperature, the measured air concentrations were significantly lower when paving with WMA for all three contaminants. Estimates based on the linear mixed model indicated that the ratios of the air concentrations measured during HMA paving to those during WMA paving were 2.77 for OC, 2.27 for asphalt vapor, and 3.09 for respirable PM, respectively. It thus appears that the air

Table 2. Concentrations of air contaminants determined by stationary sampling during paving with hot mix asphalt (HMA) and warm mix asphalt (WMA).

	HMA				WMA				*P*-value (*95 % CI*[d])	GSD for the difference between HMA and WMA	Variance component within sampling positions	Variance component between sampling positions
	N[a]	GM[b]	GSD[c]	Min–max	N	GM	GSD	Min–max				
Organic carbon (mg m^{-3})	30	0.18	2.30	0.06–1.27	30	0.09	2.32	0.01–0.32	<0.01 (0.47–0.94)	1.86	0.44	0.39
Asphalt vapor (p.p.m.)	27	0.08	4.03	0.004–0.44	27	0.04	5.57	0.001–0.52	0.02 (0.12–1.26)	4.20	1.60	0.89
Respirable fraction of PM[e] (mg m^{-3})	15	0.22	2.43	0.05–1.12	15	0.12	2.83	<0.03[f]–0.36	0.04 (0.04–1.28)	3.06	1.03	0.08
Thoracic fraction of PM (mg m^{-3})	15	0.24	2.26	0.05- 1.06	15	0.17	2.04	0.06–0.37	0.16 (−0.16–0.88	2.56	0.71	0.03
Inhalable fraction of PM (mg m^{-3})	15	0.27	2.27	0.07– 1.21	15	0.23	1.89	0.06–0.44	0.4 (−0.27–0.65)	2.31	0.45	0.12

In each experiment, three parallel samples of each contaminant were collected. The statistical significance of differences in geometric means (GMs) was tested by performing a paired t-test on ln-transformed data. The variance between and within sampling positions were calculated using variance component analysis.

[a]Number of measurements.

[b]Geometric mean.

[c] Geometric standard deviation.

[d]Confidence interval.

[e]Particulate matter.

[f]One measurement was below the LOD.

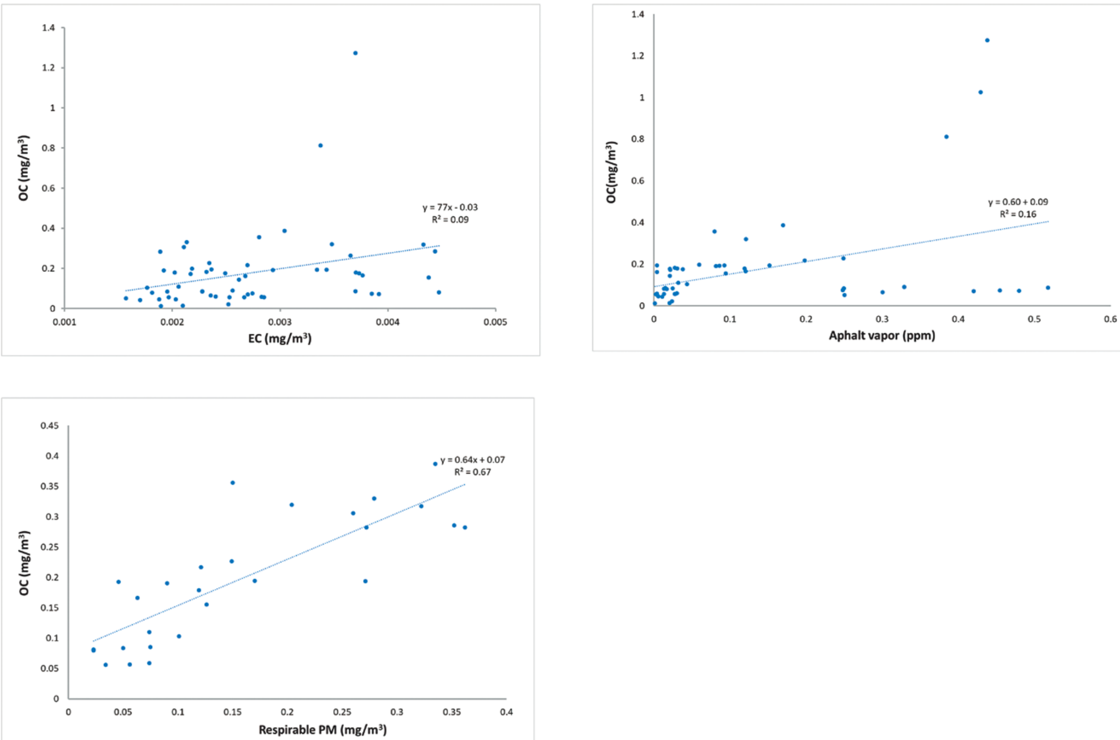

Figure 1. Associations between organic carbon (OC) and elemental carbon (EC), OC and asphalt vapor, and OC and the respirable fraction of particulate matter (PM). The regression line, regression equation, and explained variance (R^2) are shown in each case.

Table 3. A linear mixed model of the estimated difference (estimate) between the mean airborne concentration during paving with warm mix asphalt (WMA) and hot mix asphalt (HMA) (WMA was set as the reference) after adjusting for the ambient air temperature.

	Contaminant	Estimate	*P*-value	95% CI	Estimate of covariance parameters (95% CI)
All WMA	Organic carbon (mg m^{-3})	1.02	<0.01	0.67–1.37	0.39 (0.21–0.71)
All WMA	Asphalt vapor (p.p.m.)	0.82	0.02	0.14–1.49	1.14 (0.53–2.46)
All WMA	Respirable fraction of PM[a] (mg m^{-3})	1.13	<0.01	0.47–1.79	0.65 (0.31–1.34)
All WMA	Thoracic fraction of PM (mg m^{-3})	0.89	<0.01	0.34–1.45	0.49 (0.30–8.81)
All WMA	Inhalable fraction of PM (mg m^{-3})	0.68	<0.01	0.21–1.14	0.35 (0.21–0.57)
Additive WMA	Organic carbon (mg m^{-3})	0.83	<0.01	0.39–1.27	0.29 (0.13–0.64)
Additive WMA	Asphalt vapor (p.p.m.)	0.10	0.38	−0.15–35	0.05 (0.02–0.11)
FOAM WMA	Organic Carbon (mg m^{-3})	0.32	0.02	0.06–0.57	0.05 (0.02–0.12)
FOAM WMA	Asphalt vapor (p.p.m.)	0.08	0.85	−0.87–1.04	0.84 (0.32–2.22)

All data are ln-transformed. The estimates are shown together with the corresponding 95% confidence interval (CI), *P*-value, and the estimates for the random effects.

[a]Particulate matter.

concentrations of these contaminants were around three times higher when paving with HMA than with WMA after adjusting for the ambient air temperature.

When considering the results for additive and foam WMA separately, the OC air concentrations determined for the two WMA methods were both significantly lower than when using HMA. However, the air concentrations of asphalt vapor did not differ significantly from those for HMA (Table 3).

Personal sampling

Thirty samples of asphalt fumes and vapor were collected by personal sampling. While the GM asphalt vapor concentration was lower for WMA than for HMA (0.06 versus 0.07 p.p.m.), the difference was not statistically significant (Table 4). Adjusting for wind speed and air temperature did not change this. The measured asphalt fume concentrations were only above the LOD in three of the collected samples (data not shown).

Polymer-modified asphalt

One supplementary field experiment was conducted to compare paving with polymer-modified bitumen (PmB) under WMA and HMA conditions. The AM asphalt temperature was 40°C lower when using PmB WMA (134°C) than with PmB HMA (174°C). For all contaminants other than asphalt fumes, the measured air concentrations were lower when paving with PmB WMA than with PmB HMA (Fig. 2). These results were not evaluated statistically due to the small number of samples acquired.

Discussion

To the authors' knowledge, this is the first study comparing asphalt paving with HMA and WMA in terms of their impact on occupational exposure to airborne contaminants in real occupational settings.

Air concentrations of respirable PM, asphalt vapor, and OC determined by stationary sampling were significantly lower during road paving with WMA than when paving with HMA (Table 2). Personal sampling of air contaminant among screedmen showed no significant difference in exposure to asphalt vapor when paving with WMA or HMA (Table 4). The screedmen were sampled because they were willing to participate in the study, unlike other personnel such as the asphalt paver operator. Sampling of the operator might have given a better view of the differences in exposure due to using WMA instead of HMA.

When adjusted for ambient air temperature, the air concentrations were approximately three times higher when paving with HMA than WMA (Table 3). This is consistent with previously reported laboratory experiments, where emissions from asphalt were shown to depend on the temperature and volatility of the bitumen (Brandt and de Groot, 1999; Nilsson *et al.*, 2018; Mo *et al.*, 2019). Accordingly, Burstyn *et al.* suggested in 2002 that reducing asphalt temperatures could reduce occupational exposure during paving (Burstyn *et al.*, 2002). Indeed, the results presented here show that using WMA instead of HMA significantly reduces both asphalt temperatures and the concentrations of air contaminants generated during paving. The same reduction in exposure was, however, not detected in the personal samples among screedmen. This might be due to the low number of measurements or the fact that the screedmen also performed other tasks during paving such as applying adhesives to the old asphalt.

A major strength of this work is its experimental design: air samples were collected during paving with

Table 4. Air concentrations of asphalt vapor (p.p.m.) collected by personal air sampling among screedmen.

	N[a]	GM[b]	GSD[c]	Min–max	*P*-value	GSD for the difference between HMA and WMA
WMA	15	0.06	2.63	0.007–0.248		
HMA	15	0.07	3.02	0.008–0.277	0.63	3.59
Additive WMA	9	0.10	1.99	0.023–0.248		
HMA[d]	9	0.10	2.77	0.011–0.277	1.00	4.05
Foam WMA	6	0.03	2.37	0.007–0.076		
HMA[e]	6	0.04	3.05	0.007–0.134	0.44	3.18

The results of all measurements during paving with warm mix asphalt (WMA) and hot mix asphalt (HMA) are shown as well as results stratified based on the use of additive or foam WMA. The statistical significance of the observed differences in geometric mean (GM) was tested by performing a paired *t*-test *on ln-transformed data*.

[a]Number of measurements.

[b]Geometric mean.

[c]Geometric standard deviation.

[d]Corresponding road sections with additive WMA.

[e]Corresponding road sections with foam WMA.

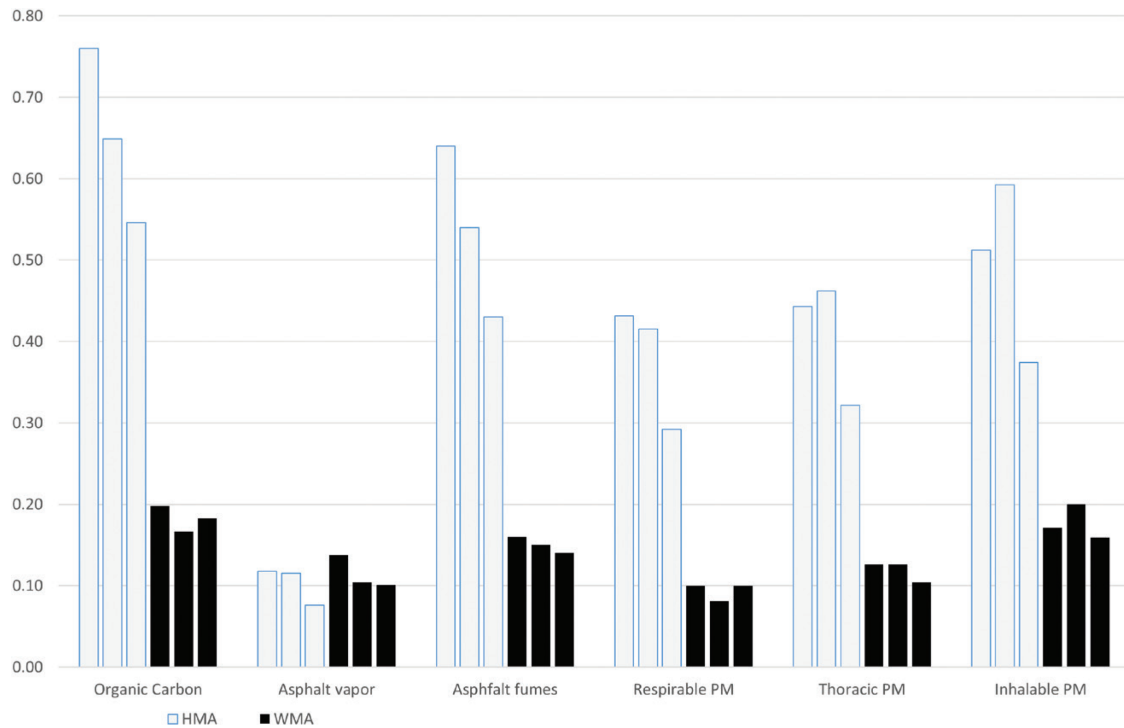

Figure 2. Individual measurements of organic carbon (mg m^{-3}), asphalt vapor (p.p.m.), asphalt fumes (mg m^{-3}), respirable particulate matter (PM) (mg m^{-3}), and thoracic PM (mg m^{-3}) and inhalable PM (mg m^{-3}) during paving with PmB HMA and PmB WMA.

WMA and HMA on the same road section during the same day. Meteorological data were also collected because the experimental design required similar weather conditions when paving with each asphalt type. Samples from one field experiment had to be excluded due to excessive wind speed. It should be noted that the chosen design has some limitations when compared to laboratory experiments or occupational hygiene studies conducted to assess more controlled and routinely performed work tasks. One such limitation is that only a few experiments could be performed due to the high costs of conducting an experimental study that permitted controlled comparisons between the two application techniques. In the experiments, paving with WMA was always done before paving with HMA. This was done to enable better temperature control of the produced asphalt at the asphalt plant when switching between WMA and HMA production. In each experiment, paving with HMA commenced approximately 5 h after paving with HMA had begun, and did not start before the surface temperature of the WMA-paved section had fallen to a level permitting the passage of traffic (<80°C). At such low asphalt temperatures, the residual emissions are expected to be so low that they would be unlikely to affect measurements during paving with HMA (Brandt and de Groot, 1999). Studying road sections close to production sites enabled better control over the asphalt's temperature upon delivery but might have yielded different results to those that would have been obtained if the asphalt had been transported over longer distances. When asphalt is to be transported over long distances, it is often overheated at the production site to ensure it remains hot enough for use upon delivery. This could cause the asphalt to be warmer during application than it was in this study. Another limitation is that many of the PM samples collected during paving with WMA and HMA had concentrations below the LOD due to the high LOD of a filter batch used in the later experiments. Nevertheless, the results presented here are valuable because it is important to complement and critically examine laboratory model experiments with field studies when practically and economically possible.

The air concentrations of respirable PM measured during paving with HMA in this study (0.22 mg m^{-3}) are similar to the previously reported values of 0.24–0.33 mg m^{-3} (Elihn *et al.*, 2008; Nilsson *et al.*, 2018; Xu *et al.*, 2018). Also worth noting is that the air concentrations of respirable, thoracic, and inhalable PM during paving with HMA were quite similar (Table 2), which may indicate that respirable PM is the predominant form of PM in the air. This is consistent with earlier studies showing that particles emitted during asphalt paving mainly have aerodynamic diameters below 1 µm (Elihn *et al.*, 2008; Nilsson *et al.*, 2018).

OC measured during paving may originate from different sources, e.g. pollen, the asphalt itself, diesel exhaust from passing traffic (traffic was allowed to pass in the open lane during paving), the paving machines, or other local sources (Burstyn *et al.*, 2002; Osborn *et al.*, 2013). EC often originates from diesel engines (Shah *et al.*, 2004). The air concentrations of EC measured in this study agree well with previous on-road measurements of EC, which are summarized in a review by Pronk *et al.* (Pronk *et al.*, 2009). Sampling was conducted at night when traffic density was low; consequently, the impact of passing traffic on the air OC concentration was also assumed to be low. Nevertheless, the OC levels were adjusted using the EC concentration, which served as a measure of the contribution of passing traffic to the OC levels. This adjustment was made possible by the use of a linear mixed model and the fact that the same asphalt-paving machines were used when paving with WMA and HMA in each field experiment. As expected, adjusting for EC did not change the estimates obtained with the linear mixed model (Supplementart Field 1). It was thus concluded that passing traffic did not contribute significantly to the OC levels in these field experiments, supporting the hypothesis that the observed differences in OC levels can be attributed to the different asphalt mixtures used for paving.

The high Pearson's correlation coefficient (0.83) and beta coefficient (0.64) calculated for the relationship between the concentrations of the respirable PM fraction and OC may indicate that a large proportion of the PM collected during paving consists of OC. Because OC measurement is a sensitive analytical technique, the OC concentration may be a useful indicator of occupational exposure during asphalt paving.

Low levels of volatile amines were detected in a few samples, and only in samples where the amine-based anti-stripping agent originated from the same supplier. This suggests that exposure to volatile amines during asphalt paving may depend primarily on factors other than the asphalt temperature (Xu *et al.*, 2018). One such factor could be the content of residual amines in the bitumen originating from the production of the amine-based anti-stripping agent.

The air concentrations of almost all studied contaminants were lower when paving with PmB WMA instead of PmB HMA (Fig. 2). The differences in the air concentrations measured in this field study exceeded those reported previously. In previous experiments, HMA was applied at 145–165°C, whereas the asphalt temperature was 170–180°C during PmB HMA paving in this work. No firm conclusions can be drawn from a single field experiment. However, these results may indicate that the potential for reducing airborne contaminant concentrations generated during paving may be greatest when considering asphalts that are normally used at particularly high temperatures, such as the PmB asphalt (Brandt and de Groot, 1999; Rubio *et al.*, 2012; Nilsson *et al.*, 2018; Mo *et al.*, 2019). These results could be further critically examined in laboratory experiments that are less costly to perform than the field experiments presented here.

Jørgensen has shown that there are no significant differences in road durability between the HMA and WMA techniques used in this work (Jørgensen, 2017). Furthermore, the lower temperatures used when paving with WMA were suggested to be more environmentally friendly due to reduced energy consumption (Rubio *et al.*, 2013). Finally, the present study shows that WMA application techniques are preferable to HMA because they generate lower levels of airborne contaminants in the working atmosphere, however, the impact on personal exposure should be further studied.

Conclusion

This study shows that paving with WMA generates lower air concentrations of the respirable fraction of PM, OC, and asphalt vapor than paving with HMA. Because exposure to airborne contaminants generated during asphalt paving is associated with adverse health effects among asphalt pavers, replacing traditionally used HMA with WMA may have appreciable future health benefits. This study also suggests that measurements of OC may be a useful general marker of exposure to air contaminants generated during asphalt paving.

Funding

The Confederation of Norwegian Enterprises is acknowledged for financial support of the study.

Conflict of interest

The authors declare no conflict of interest.

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