Construction and Building Materials 418 (2024) 135453

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Comparison of energy and environmental performance between warm and hot mix asphalt concrete production: A case study

G. Ferrotti [a], E. Mancinelli [b,*], G. Passerini [b], F. Canestrari [a]

[a] Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona 60131, Italy
[b] Department of Industrial Engineering and Mathematical Sciences, Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona 60131, Italy

A R T I C L E I N F O

Keywords:
Warm mix asphalt
Hot mix asphalt
Energy consumption
Emissions
Reclaimed asphalt
Sustainability

A B S T R A C T

The use of additives to produce warm bituminous mixtures in asphalt pavements gives the possibility to decrease temperatures with positive implications on energy consumption, and on emissions of greenhouse gases and airborne pollutants. This study investigates the changes in energy and environmental performance of an asphalt plant switching from hot to warm asphalt concrete production. A full-scale trial section was constructed in an Italian motorway with recycled bituminous mixtures containing SBS polymer modified bitumen. Reference hot mix asphalts (HMAs) mixed at 170 °C were compared with warm mix asphalts (WMAs) mixed at 130 °C with different chemical additives. Calculations and analysis were performed considering three production phases during which the production technologies (HMA and WMA) and the mixture types varied in temperatures, mixing duration, and quantity of virgin materials employed. Energy performance was calculated through values provided by the asphalt plant operator and thermodynamic equations. Emissions of CO2 were calculated based on energy consumption and emission factors reported in the literature for the Italian energy mix. Airborne pollutants were measured at the stack of the dryer drum. The results showed that for each mixture type, a reduction of 40 °C in the production temperature corresponds to 15% lower thermal energy values for the drying/heating of the aggregates, with consequent lower consumption of fuel oil. The drying/heating of aggregates for WMA lead to lower emissions of particulate matter, NOx, and VOCs compared to HMA.

1. Introduction

The road sector has seen an impetus in the search for production technologies more efficient in energy and materials consumption whilst reducing emissions of harmful substances to the atmosphere. This is not only due to an increase in environmental awareness in the management of transportation infrastructures [25] and potential economic benefits [1,26,29,50] but also to more stringent norms in greenhouse gases emissions enforced by the European Union [15].

A branch of research is focusing on replacing conventional bituminous materials with other products having comparable or enhanced mechanical properties but lower energy consumption [9] and emissions [10]. An example is represented by warm mix asphalts (WMAs), which allow a reduction of production, laying and compaction temperatures from 20 to 40 °C with respect to hot mix asphalts (HMAs). WMA technology also allows the increase of reclaimed asphalt (RA) amount included in the recycled asphalt mixtures thanks to a lower aging of the bitumen in the production phase, in accordance with the circular economy principle [19]. Foaming technologies, chemical or organic additives [8] can be employed for WMA production, allowing to reach a proper mixture workability at lower temperatures.

The WMA technology is very promising but is currently not widespread worldwide as reported by the European Asphalt Pavement Association [13] which shows that in the European Countries the percentage of WMA production with respect to the total asphalt concrete production is generally much lower than 10%, except in Norway, Portugal, and France where the percentages are 27%, 15% and 13%, respectively. This is probably because there are several aspects under study that should be explored in more detail such as long-term performance in the field [22,40] or variations in energy/fuel consumption and associated emissions of airborne pollutants and greenhouse gases in relation to the considered production technology (HMA or WMA).

In terms of fuel consumption, West et al. [50] demonstrated that the fuel savings achieved by switching from HMA to WMA production are on

* Correspondence to: DIISM/UNIVPM, Ancona 60131, Italy
E-mail addresses: g.ferrotti@staff.univpm.it (G. Ferrotti), e.mancinelli@univpm.it (E. Mancinelli), g.passerini@staff.univpm.it (G. Passerini), f.canestrari@staff.univpm.it (F. Canestrari).

https://doi.org/10.1016/j.conbuildmat.2024.135453
Received 9 October 2023; Received in revised form 7 February 2024; Accepted 12 February 2024
Available online 19 February 2024

average due to lower mixing temperature (50%), lower casing loss (32%), and lower stack temperature (18%).

As for energy and emissions, it has been shown that the drying/heating of aggregates in the drum is the operation with the highest energy consumption [2] and ducted emissions [46,50] in batch mix plants. However, there is not always a direct correspondence between decrease in temperature production and reduction of airborne pollutant emissions at the asphalt plant. Indeed, different pollutants have different emission characteristics as demonstrated by Paranhos and Petter [30] who pointed out that variations in emissions are not only due to design variables (e.g., final temperature of the asphalt concrete mixture) or parameters under control of the operator (e.g., production rate, burner flow rate, and fuel consumption), but also to random variables such as quality of fuel and moisture content of aggregates. As an example, to produce WMA (with a chemical additive and a surfactant modified bitumen) at 140 °C, Sol-Sánchez et al. [39] reported a reduction in the total demand of energy (17%), in the CO2 and NOx as well as an increase in the total organic carbon and CO emissions, with respect to HMA produced at 176 °C. Similarly, West et al. [50], measuring stack emissions in a portable parallel flow drum plant burning fuel oil, showed no variations in NOx emissions, higher CO but lower volatile organic compunds (VOCs) and SO2 emission rate per ton of WMA, produced with a chemical additive, compared to HMA (mixed at 132 °C and 149 °C, respectively). A state of the art of WMA in Europe [12] listed reductions in energy and fuel consumptions as well as in emissions of CO2 and airborne pollutants such as SO2, VOCs, NOx, particulate matter (PM) and CO, contrarily to Sol-Sánchez et al. [39] and West et al. [50]. However, d'Angelo et al. [12] and Anthonissen and Braet [4] observed that the emissions of CO are strictly related to the burner setting at the asphalt plant, allowing to explain the differences in the CO pollutant emission between these different studies.

For comparing environmental performance of different asphalt production technologies or production conditions, other researchers theoretically calculated heat energy and related fuel consumption [2,21,3,37,38,50,7], emissions of CO2 or other greenhouse gases [1,5,6,20,24,34,35,43] and airborne pollutants [33], based on thermodynamic equations.

To analyse the potential environmental impacts of part or all of the asphalt production process (e.g., from materials production to the decommissioning of the infrastructure), life cycle assessments are often performed to assess potential drawbacks in implementing new asphalt technologies ([18,32,47,49], to cite a few studies). However, studies based on life cycle assessments are difficult to compare because of differences in process stages, road design, and environmental externalities [4,51].

2. Aim and objectives

This paper aims at investigating the changes in energy and environmental performance of an asphalt plant shifting from hot to warm asphalt concrete production. As a case study, the authors present the production of three different mixture types (a dense-graded DG asphalt concrete for base course, a DG asphalt concrete for binder course and an open-graded OG asphalt concrete for porous wearing course) with different production technologies (WMA and HMA) for the reconstruction of a full-scale trial section of an Italian motorway [41] and [42].

To analyze the differences in energy consumption and emissions of CO2 at the asphalt plant, three production phases have been considered (i.e., drying/heating of aggregates, heating of bitumen, and mixing), during which the production technologies and the mixture types differ in terms of temperatures involved, mixing duration, and quantity of virgin materials employed (Fig. 1). Peng et al. [31] estimated that about 90% of the greenhouse gases emissions during production and construction phases of an asphalt pavement are attributable to the heating of aggregates and bitumen, and to the mixture mixing.

Energy performance is calculated through thermodynamic equations by using values provided by the asphalt plant operator. Environmental performance, in terms of emissions of CO2 and airborne pollutant (i.e., CO, VOCs, SOx, particulate matter PM, and NOx), are based on calculations and measurements, respectively. Specifically, emissions of CO2 were calculated based on energy consumption and emission factors reported in the literature for the Italian energy mix, whereas measurements of airborne pollutants were performed at the dryer drum stack [41].

The functional unit consists in 1 ton of WMA or HMA. Therefore, results are presented with respect to the production of 1 ton of WMA and HMA of DG for base course, DG for binder course and OG for porous wearing course.

3. Full-scale trial section and asphalt concrete production

In 2016, the reconstruction of an 800 m section of an Italian motorway involved the production and laying of recycled bituminous hot and warm mixtures. This full-scale trial section was characterized by the reconstruction of three layers (base, binder and wearing) in four sub-sections (each 200 m long). The first sub-section was constructed with three HMA mixtures mixed at 170 °C: a dense-graded DG asphalt concrete for base course, a DG asphalt concrete for binder course and an open-graded OG asphalt concrete for porous wearing course (Fig. 2). The other three sub-sections were constructed with the same layers (base, binder and porous wearing) by employing WMA mixtures mixed at 130 °C. Each WMA sub-section was realized with a different chemical additive. Specifically, an additive mainly composed of ammine substances which act as surfactants and adhesion enhancers, an additive containing

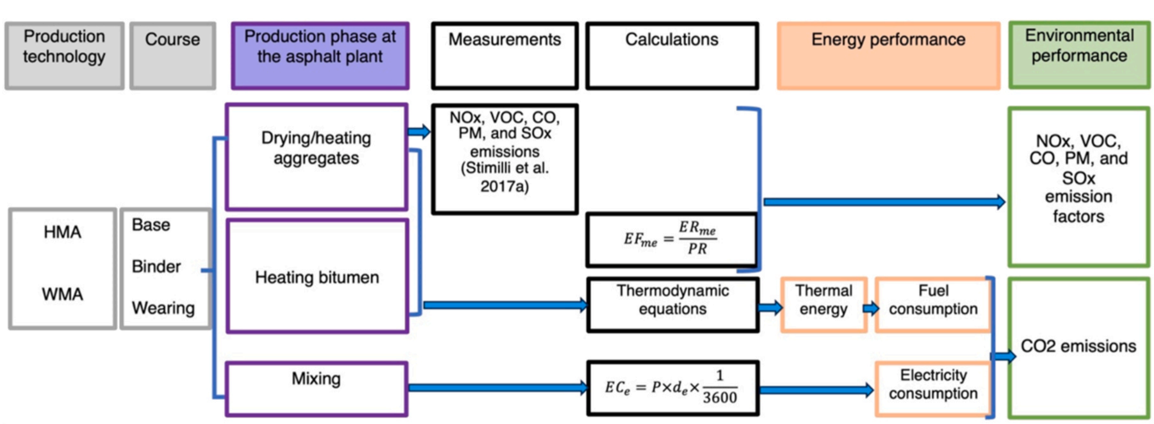

Fig. 1. Flow chart of the methods and objectives of this study.

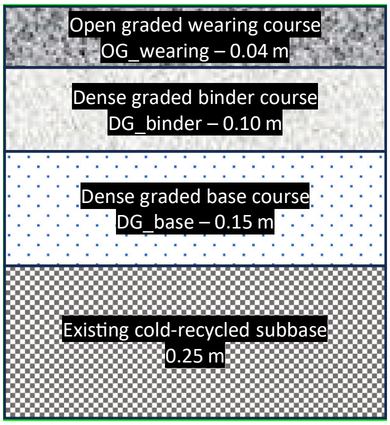

Fig. 2. Typical cross section and nominal thickness for each layer.

alkylates and fatty acids which act as viscous regulators and an additive that acts as viscous regulator, similarly to the second one but with a different chemical composition, were used.

The mixtures employed for base courses were coded as DG_base, those for binder courses were coded as DG_binder and those for wearing courses were coded as OG_wearing (Fig. 2).

The type and content of styrene- butadiene-styrene (SBS) polymer modified bitumen (i.e. 3.8% of SBS by bitumen weight), the aggregate grading curves and the reclaimed asphalt (RA) contents used in this study are those typically employed for construction and maintenance activities in the Italian motorways. Table 1 shows the characteristics of the materials used. Further details can be found in Stimilli et al. [41] for an in deep description and analysis of the full-scale trial section, and in Stimilli et al. [42] for a comparison in terms of mechanical and rheological performance provided by the different mixture types produced with the different technologies.

The considered asphalt plant is a discontinuous mix plant with an average annual production of about 60,000 tons of asphalt concrete. The average production rate of HMA is of 100 t/h in cold weather periods and 140 t/h in warm weather periods.

The RA is added to the mixtures at ambient temperature during the mixing phase. To account for the conduction heat transfer between virgin aggregates and RA, aggregates must be superheated. This superheating depends, firstly, on the RA content in the mixture, providing different aggregate heating temperatures for the different mixture types (Table 2). Furthermore, this superheating depends on moisture content of aggregates and mean ambient temperature, allowing to perform calculations considering two different annual periods: *Period 1* characterized by unfavourable conditions in terms of moisture and temperature of the aggregates and *Period 2* characterized by more favourable moisture and temperature conditions. The average aggregate heating temperatures of each period and for each mixture type were provided by the asphalt plant operator (Table 2), whereas the mean ambient temperatures were calculated and reported in Table 3. Specifically, the ambient temperature was obtained considering the surface temperature (2 m) averaged over *Period 1* (i.e., from December to February) and *Period 2* (i.e., from June to August) for a 11-year period (i.e., from 2010 to 2020), based on monthly data related to the location of the asphalt plant, downloaded from the 'Photovoltaic geographical information system' in the website of the European Commission (https://re.jrc.ec.europa.eu/pvg_tools/en/).

The energy sources of the asphalt plant consist in low-sulphur crude oil for the dryer drum, and liquified petroleum gas (LPG) for heating the bitumen storage tank (heated 365 days/year). Moreover, mixing is done by electricity from the national grid.

4. Data and calculations

As above-mentioned, the calculation of the energy involved in the production of asphalt concrete mixtures is divided into three different phases, i.e., drying/heating aggregates, heating bitumen, and mixing. These production phases are considered because they cover most of the energy needs at the asphalt plant [31]. These production phases are characterized by differences between HMA and WMA in terms of mass of virgin materials, production temperatures, and duration of the mixing.

For drying/heating aggregates and heating bitumen, thermal energy calculations were performed considering the thermodynamic properties of the materials, the variations in temperatures and moisture content within the considered annual period (1 or 2), and the different aggregate types and related quantities used for mixture production.

Electrical energy consumption is calculated based on the power of the motor of the mixer and the different durations of the HMA and WMA mixing phases (26 and 30 s, respectively).

Calculations of fuel consumption and related CO2 emissions consider emission factors and calorific values reported in the literature according to the energy mix in Italy.

The airborne pollutants emissions at the stack of the drying drum were measured, as reported in a previous study by Stimilli et al. [41]. The corresponding emission factors were calculated.

4.1. Thermal energy for drying/heating aggregates and heating bitumen

In this section, the energy consumption at the asphalt plant was theoretically calculated. It does not account for the thermal energy requirements of the start-up phase but considers the thermal energy related to the process of drying/heating aggregates and heating bitumen and the casing losses which can strongly affect the energy consumption. Indeed, differences between theoretical and real thermal requirements for asphalt concrete production may rise from the thermal energy dissipated via the case of the asphalt plant to the atmosphere, as reported by Androjić et al. [2]. Specifically, they observed up to 13% lower values of theoretical thermal energy compared to the real thermal energy spent in the drying/heating of aggregates because of a variety of factors, such as discontinuity in work, quality of fuel, and efficiency of the equipment. Other studies reported values of correction factor for casing losses equal to 27% [34] or 17.8% [5] of the thermal energy for drying/heating aggregate and heating bitumen. Furthermore, Androjić et al. [2] observed that a part of the thermal energy is dissipated through the loss of the finer fractions of the heated material during dedusting process.

In this study, the variation in energy consumption depending on the annual period has been accounted for different (i) mean ambient temperatures, (ii) moisture content of aggregates [2,3], and (iii) mixture production temperatures for period 1 and 2. Moreover, for each mixture type, different (a) mass of virgin aggregates, (b) calorific values depending on limestone or siliceous aggregates, and (c) mass of virgin

Table 1
Characteristics of the materials used.

Layer	Type of asphalt concrete	Layer code	RA content (aggr.weight) [%]	Total bitumen content [%]	Thickness [m]	Average air void content [%]
Base	Dense graded	DG_base	30	4.50	0.15	2.1
Binder	Dense graded	DG_binder	25	4.80	0.10	3.3
Wearing	Open graded	OG_wearing	15	5.25	0.04	17.3

Table 2
Mixture and aggregate heating temperature for different mixture types and production technologies.

Mixture type	Mixture heating temperature in °C [in K]		Aggregate heating temperatures in °C [in K]			
			Period 1		Period 2	
	HMA	WMA	HMA	WMA	HMA	WMA
DG_base	170 [443.15]	130 [403.15]	240 [513.15]	200 [473.15]	220 [493.15]	180 [453.15]
DG_binder	170 [443.15]	130 [403.15]	230 [503.15]	190 [463.15]	210 [483.15]	170 [443.15]
OG_wearing	170 [443.15]	130 [403.15]	200 [473.15]	160 [433.15]	190 [463.15]	150 [423.15]

Table 3
Mean ambient temperature and moisture content of aggregates.

Parameter	Period 1	Period 2
Mean ambient temperature in °C [in K]	[a]6.6 [279.7]	[a]24.3 [297.48]
Mean moisture content of aggregates [%]	[b]3	1.5

[a] , Own elaboration based on data from European Commission (https://re.jrc.ec.europa.eu/pvg_tools/en/)
[b] , [1,5,34]

bitumen have been considered.

The energy consumption for drying/heating aggregates ($TE_{a,j}$) and heating bitumen ($TE_{b,j}$) at the asphalt plant were calculated as follows [1,33,34]:

$$TE_{a,j} = E_{da,j} \times (1 + CL) \tag{1}$$

$$TE_{b,j} = E_{hb,j} \times (1 + CL) \tag{2}$$

where:$TE_{a,j}$ = annual mean thermal energy [J] for heating the aggregates of the j-mixture (j = DG_base, DG_binder, and OG_wearing);$TE_{b,j}$ = annual mean thermal energy [J] for heating the bitumen of the j-mixture;$E_{da,j}$ = annual mean energy [J] for drying aggregates for the j-mixture;CL = casing losses [%] assumed equal to 27% according to [34];$E_{hb,j}$ = annual mean energy [J] for heating bitumen for the j-mixture;

The annual mean energy for drying aggregates $E_{da,j}$ can be calculated as mean value between the energies for drying aggregates in the two *i*-periods (i = 1 or 2), as follows:

$$E_{da,j} = \frac{1}{2}\sum_i (E_{ha,ij} + E_{hw,ij} + E_{vw,ij} + E_{hs,ij}) \tag{3}$$

$$E_{ha,ij} = Q_{a,j} \times m_{a,j} \times (t_{a,ij} - t_{amb,i}) \tag{4}$$

$$E_{hw,ij} = Q_w \times \left(\frac{h_i}{100}\right) \times m_{a,j} \times (373.15 - t_{amb,i}) \tag{5}$$

$$E_{vw,ij} = L \times \left(\frac{h_i}{100}\right) \times m_{a,j} \tag{6}$$

$$E_{hs,ij} = Q_s \times \left(\frac{h_i}{100}\right) \times m_{a,j} \times (t_{a,ij} - 373.15) \tag{7}$$

where:$E_{ha,ij}$ = energy [J] for heating the aggregates of the j-mixture in the *i*-period;$E_{hw,ij}$ = energy [J] for heating the water of the aggregates of the j-mixture in the *i*-period;$E_{vw,ij}$ = energy [J] for vaporizing the water of the aggregates of the j-mixture in the *i*-period;$E_{hs,ij}$ = energy [J] for heating the steam of the j-mixture in the *i*-period;$Q_{a,j}$ = specific heat of aggregates [J/kgK] of the j-mixture (i.e., siliceous for OG_wearing, and limestone for DG_base and DG_binder) (Table 4);$m_{a,j}$ = mass of virgin aggregates [kg] in the drying drum of the j-mixture (Table 5);$t_{a,ij}$ = heating temperature [K] of aggregates of the j-mixture in the *i*-period (Table 2);$t_{amb,i}$ = mean ambient temperature [K] in the *i*-period (Table 3);Q_w = specific heat of water [J/kgK] (Table 4);h_i = moisture content [%] of aggregates in the *i*-period (Table 3);373.15 = water boiling temperature [K] (= 100 °C);L = Latent heat of vaporizing water [J/kg] (Table 4);Q_s = specific heat of steam at constant pressure and 373.15 K [J/kgK] (Table 4)

Table 4
Temperatures and thermodynamic properties of the materials involved in the drying/heating of aggregates, and heating of bitumen.

Symbol	Unit	Description	Value	Reference
t_b	K (°C)	Heating temperature of bitumen	443.15 (170)	Asphalt plant
$Q_{a,j}$	J/kgK	Specific heat of limestone (DG_base, DG_binder)	880	[35]
		Specific heat of siliceous (OG_wearing)	860	[35]
Q_w	J/kgK	Specific heat of water at constant pressure and 293.15 K (20 °C)	4183	http://pcfarina.eng.unipr.it/Public/Termofluidodinamica/TABELLE_fta.pdf
Q_s	J/kgK	Specific heat of steam at constant pressure and 373.15 K (100 °C)	2044	http://pcfarina.eng.unipr.it/Public/Termofluidodinamica/TABELLE_fta.pdf
Q_b	J/kgK	Specific heat of bitumen	2093.4	[1,34]
L	J/kg	Latent heat of vaporizing water	2.25*10^6	[48]
LCV_{FO}	J/t	Lower calorific value of fuel oil in Italy	41.072*10^9	[27]
LCV_{LPG}	J/t	Lower calorific value of liquified petroleum gas in Italy	45.858*10^9	[27]

Table 5
Mass of reclaimed asphalt (RA), virgin aggregates and bitumen in 1 ton of asphalt mixture.

Symbol	Unit	Description	Mixture type		
			DG_base	DG_binder	OG_wearing
$m_{a,j}$	kg	Mass of virgin aggregates	680	724	813
$m_{b,j}$	kg	Mass of virgin bitumen	29	35	44
m_{RA}	kg	Mass of RA	291	241	143

The annual mean energy for heating bitumen $E_{hb,j}$ can be calculated as mean value between the energies for heating bitumen in the two *i*-periods (i = 1 or 2), as follows:

$$E_{hb,j} = \frac{1}{2}\sum_i E_{hb,ij} \tag{8}$$

$$E_{hb,ij} = Q_b \times m_{b,j} \times (t_b - t_{amb,i}) \tag{9}$$

where:$E_{hb,ij}$ = energy for heating bitumen of the j-mixture in the *i*-period;Q_b = specific heat of bitumen [J/kgK] (Table 4);$m_{b,j}$ = mass of virgin bitumen [kg] for the j-mixture (Table 5);t_b = heating temperature [K] of virgin bitumen (Table 4).

4.2. Fuel consumption related to the thermal energy for drying/heating aggregates and heating bitumen

Fuel consumption for the thermal energy involved in drying/heating aggregates and heating bitumen at the asphalt plant is calculated as follows:

$$FC_{a,j} = \frac{TE_{a,j}}{LCV_{FO}} \times 10^3 \quad (10)$$

$$FC_{b,j} = \frac{TE_{b,j}}{LCV_{LPG}} \times 10^3 \quad (11)$$

where:$FC_{a,j}$ = fuel consumption [kg] for the thermal energy for drying/heating aggregates of the j-mixture (j = DG_base, DG_binder, and OG_wearing);$FC_{b,j}$ = fuel consumption [kg] for the thermal energy for heating bitumen of the j-mixture;$TE_{a,j}$ = annual mean thermal energy [J] for drying/heating aggregates (Eq. 1) of the j-mixture;LCV_{FO} = lower calorific value [J/t] of fuel oil in Italy for the year 2022 (Italian Ministry of the Environment – MASE [27], Table 4);10^3 = conversion factor from ton to kg;$TE_{b,j}$ = annual mean thermal energy [J] for heating bitumen (Eq. 2) of the j-mixture;LCV_{LPG} = lower calorific value [J/t] of LPG in Italy for the year 2022 (MASE [27] , Table 4).

4.3. Electricity consumption during mixing phase

The electricity consumption relative to the mixing of 1 ton of HMA and WMA is calculated as a portion of the electricity spent in a mixing cycle for an average mass of 2.45 tons of asphalt concrete. The electricity spent in a mixing cycle is estimated as follows:

$$EC_e = P \times d_e \times \frac{1}{3600} \quad (12)$$

where:EC_e = electricity consumption [kWh] during the mixing cycle of the *e*-technology (e = HMA, WMA);P = power [kW] of the three-phase asynchronous electric motor of the mixer (P = 37 kW);d_e= duration [s] of the mixing cycle of the *e*-technology (i.e., 26 s for HMA and 30 s for WMA);$\frac{1}{3600}$ = conversion factor [h/s] from seconds to hours.

4.4. Emissions of CO2 for aggregate drying/heating and bitumen heating

Emissions of CO2 related to the consumption of fuel for drying/heating aggregates and heating bitumen is calculated as follows:

$$ECO2_{a,j} = FC_{a,j} \times EFCO2_{FO} \quad (13)$$

$$ECO2_{b,j} = FC_{b,j} \times EFCO2_{LPG} \quad (14)$$

where:$ECO2_{a,j}$ = emissions [kg] of CO2 related to the consumption of fuel oil for drying the aggregates of the j-mixture (j = DG_base, DG_binder, and OG_wearing);$FC_{a,j}$ = fuel consumption [kg] for drying/heating aggregates of the j-mixture (Eq. (10));$EFCO2_{FO}$ = CO2 emission factor (i.e., 3.143 $kgCO_2$/kg-fuel) for fuel oil in 2022 in Italy [27].$ECO2_{b,j}$ = emissions [kg] of CO2 related to the consumption of LPG for heating bitumen of the j-mixture;$FC_{b,j}$ = fuel consumption [kg] for heating bitumen of the j-mixture (Eq. (11));$EFCO2_{LPG}$ = CO2 emission factor (i.e., 3.026 $kgCO_2$/kg-fuel) for LPG in 2022 in Italy [27].

4.5. Calculation of CO2 emissions during the mixing phase

Emissions of CO2 related to the consumption of electricity during the mixing phase is estimated as follows:

$$ECO2_{m,e} = EC_e \times EFCO2_{eng} \quad (15)$$

where:$ECO2_{m,e}$ = emission [kg] of CO2 relative to the consumption of electricity for the mixing of 1 ton of mixture produced with the *e*-technology;EC_e = electricity consumption [kWh] during the mixing cycle of the *e*-technology (Eq. (12));$EFCO2_{eng}$ = CO2 emission factor (i.e., 0.2457 $kgCO_2$/kWh) for electricity consumption from the Italian national grid according to ISPRA [23].

4.6. Airborne pollutants emitted during drying/heating aggregates

Table 6 summarizes the mass emission of airborne pollutants measured at the asphalt plant during the measurement campaign [41], performed according to Italian standards. Briefly, measurements were done at the outlet of the bag filter of the aggregates drying room, with the asphalt plant operating in steady conditions during the production of HMAs and WMAs for the full-scale trial section construction. Following sample conditioning without dilution, the different gas analyzers evaluated the concentrations of interests through various techniques, namely infrared and ultraviolet adsorption, chemiluminescence, fluorescence, chromatography and spectrography.

In this study, only the emissions related to the production of the mixture DG_base were analysed, considering that both HMA and WMA were produced at a production rate (PR) of 140 ton/h. To investigate the impact of the reduction in production temperatures, measurements of emissions were performed at similar meteorological conditions (e.g., air temperature, and relative humidity) and asphalt plant configuration.

The measured mass emissions rates (ER) of airborne pollutants (Table 6) can be normalized with the production rate (PR) to make meaningful comparisons between HMA and WMA test measurements [50]. Thus, for each emission test, emission factors (EF_{me}, g/ton-AC) were calculated for the m-pollutant (m = NOx, VOCs, CO, PM, and SOx) for the DG_base of the *e*-technology (*e* = HMA or WMA) as follows:

$$EF_{me} = \frac{ER_{me}}{PR} \quad (16)$$

where:ER_{me} = mass emission [g/h] of m-pollutant for the *e*-technology (Table 6);PR = production rate of asphalt concrete (AC) for base course (140 ton-AC/h) during the measurements of airborne pollutant emissions.

5. Results and discussion

To analyze differences in energy consumption and emissions of CO2 at the asphalt plant during the production of the different mixture types (DG_base, DG_binder, and OG_wearing) with HMA or WMA technologies, only the production phases which differ in terms of temperatures involved, mixing duration, or mass of virgin materials have been considered.

Table 6
Mass emissions of airborne pollutants measured at the stack of the aggregates drying room for DG_base of HMA and WMA and technical standards. Data refer to a measurement campaign presented in the work by [41].

Airborne pollutant	Standard	Mass emissions ER [g/h]	
		HMA_{base}	WMA_{base}
NOx	Italian D.M. 25/8/2000	2547	1981
VOCs	UNI EN 12619	429	280
CO	Italian D.M. 25/8/2000	42073	51329
PM	UNI EN 13284	486	400
SOx	Italian D.M. 25/8/2000	5316	5350

5.1. Thermal energy for drying/heating aggregates and heating bitumen

Fig. 3 shows the thermal energy for drying/heating aggregates and heating bitumen for producing 1 ton of DG_base, DG_binder, and OG_wearing with HMA technology or WMA technology.

For each mixture, the values of thermal energy for drying/heating aggregates are higher by up to 0.04 GJ for HMA production compared to WMA production (Fig. 3a).

Due to lower mixing temperatures (130°C for WMA vs. 170°C for HMA), the values of thermal energy for drying/heating aggregates decrease in the range 14.6–16.6% for the WMA materials compared to the HMA ones. This is in line with the study performed by Almeida-Costa and Benta [1], who showed that the thermal energy for heating/drying aggregates to produce a base course decreased by about 20% for a reduction in the mixing temperature of 46 °C (WMA with chemical additive vs. HMA). Calabi-Floody et al. [7] estimated 13% lower thermal energy consumption for a decrease in production temperature of 30 °C for WMA compared to HMA. Slightly higher reductions in energy consumption were found by Sol-Sánchez et al. [39], who highlighted a decrease of about 35% for a production temperature reduction of 36 °C (WMA with surfactant additive vs. HMA).

The thermal energy employed for heating the virgin bitumen up to 170 °C is shown in Fig. 3b. Since the quantity of virgin bitumen employed for the different mixture types is the same for both WMA and HMA (Table 5), no differences between WMA and HMA were observed. In terms of pavement layer, the OG_wearing has the highest thermal energy spent for heating bitumen (Fig. 3b) due to the highest mass of virgin bitumen added (Table 5). These results are comparable with the thermal energy per ton of asphalt mixture calculated in previous studies. Specifically, Almeida-Costa and Benta [1] estimated 0.017 GJ for bitumen heating at 170 °C, whereas for drying/heating aggregates for base courses, they obtained 0.21 GJ for HMA with an aggregate temperature of 160 °C and 0.16 GJ for WMA with a chemical additive and an aggregate temperature of 114 °C. Analogously, Siverio Lima et al. [37] estimated the thermal energy for heating bitumen and drying/heating aggregates from 0.253 to 0.269 GJ per ton of HMA (base, binder, and wearing course) with different quantities of RA and mixing temperatures in the range between 190—220 °C. Furthermore, Siverio Lima et al. [38] calculated a thermal energy of 0.227 GJ per ton of wearing course with mixing temperature of 160 °C.

Fig. 4 shows the percentage energy required for heating aggregates (Eha), heating water (Ehw), vaporizing water (Evw) of the aggregates, heating steam (Ehs), and heating bitumen (Ehb), calculated with Eqs. (4), (5), (6), (7), and (9) respectively. Different percentages of energy contributions can be observed for the different mixture types within the same production technology and for the different production technologies within the same mixture type. However, irrespective of the production technology and mixture type, the energy ranks as follows: Eha > Evw > Ehb > Ehw > Ehs. These findings are comparable with the calculations reported by Sukhija et al. [43] for HMA at 163 °C and WMAs produced with different technologies in the temperature range 141–158 °C.

5.2. Fuel consumption for drying/heating aggregates and heating bitumen

Fig. 5 shows the consumption of fuel oil for drying/heating aggregates and LPG for heating bitumen per ton of HMA or WMA. Fuel consumption is calculated according to Eqs. (10) and (11).

Consumptions of fuel oil and LPG reflect the thermal energy estimated in Fig. 3. For the different mixture types, fuel oil consumption slightly varies within each production technology, from 5.34 to 5.48 kg for HMAs and in the range 4.56–4.65 kg for WMAs (Fig. 5a). Thus, WMA provided approximately 0.8–0.9 kg lower values of fuel oil consumption for drying/heating aggregates than HMA, corresponding to a reduction of about 15%, regardless of mixture type. The heating of bitumen requires from 0.26 to 0.39 kg of LPG for 1 ton of the different mixture types (Fig. 5b).

These results are comparable with the consumption of fuel oil estimated by Almeida-Costa and Benta [1] for producing 1 ton of HMAs at 170 °C (5.2–5.4 kg) and WMAs at 124 and 150 °C (4.2 and 4.9 kg, respectively). Analogously, Mohammad et al. [28] recorded about 13% lower fuel oil consumption for a decrease in temperature production of 19–28 °C by employing a chemical additive.

5.3. Emissions of CO2 from drying/heating aggregates and heating bitumen

Fig. 6 shows CO2 emissions related to the consumption of fuel oil for drying/heating aggregates and LPG for heating bitumen for producing 1 ton of the three different mixture types with the two different production technologies. Emissions of CO2 are calculated according to Eqs. Eqn 13 and Eqn 14 and reflect the estimated consumption of fuel oil and LPG.

Fig. 6a shows that CO2 emissions from drying/heating aggregates slightly vary for each mixture type, with values between 16.8 and 17.2 kg to produce 1 ton of HMA and between 14.3 and 14.6 kg for WMAs. Thus, WMA provided approximately 2.4–2.9 kg lower CO2 emissions for drying/heating aggregates than HMA, corresponding to a reduction of about 15%, regardless of the mixture type.

Emissions of CO2, related to LPG consumption for heating the bitumen used to produce 1 ton of asphalt mixture, are in the range

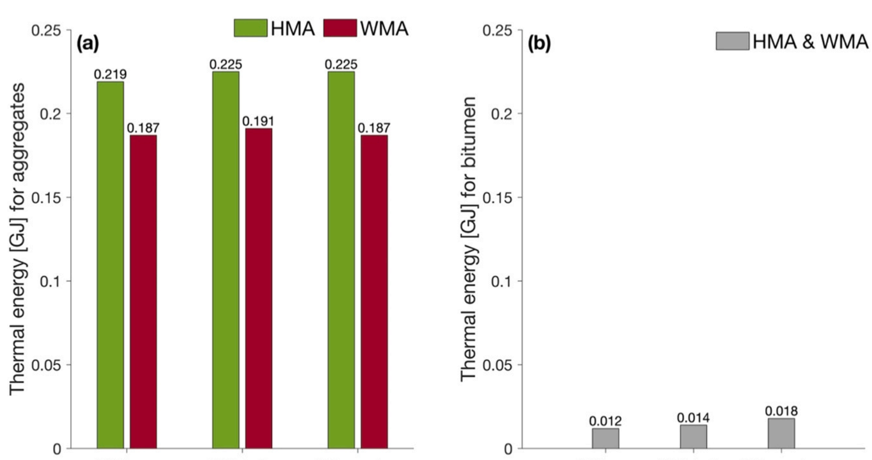

Fig. 3. Thermal energy for (a) drying/heating aggregates, and (b) heating bitumen for 1 ton of different mixture types prepared with HMA technology or WMA technology.

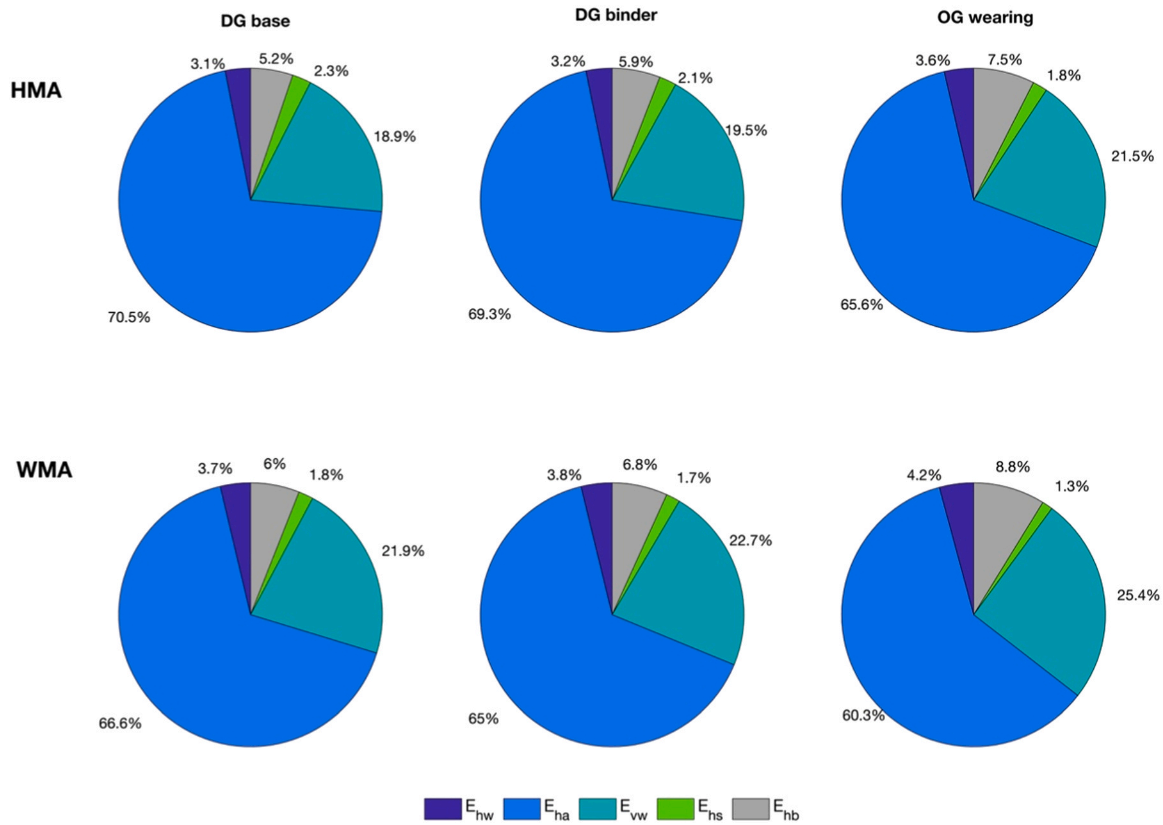

Fig. 4. Contribution in percentage of energy for heating bitumen (Ehb), heating the aggregates (Eha), heating water (Ehw) and vaporizing water (Evw) of the aggregates, heating steam (Ehs) for different mixture types and production technologies.

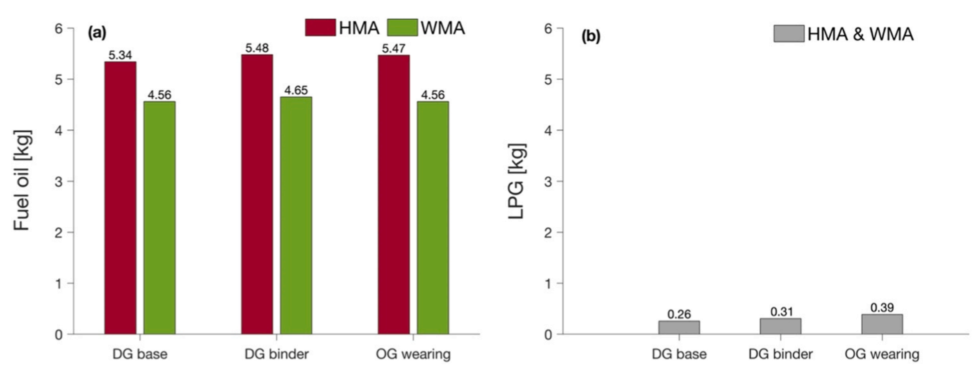

Fig. 5. Consumption of (a) fuel oil, and (b) liquified petroleum gas (LPG) for 1 ton of different mixture types and production technologies.

0.8–1.2 kg (Fig. 6b), depending on the mixture type.

For the different mixture types and asphalt technologies, the process of drying/heating aggregates accounted for 92–96% of the total emissions of CO2, given by drying/heating aggregates and heating bitumen. This is in line with what observed by Li et al. [24] who estimated for drying/heating aggregates between 94% and 97% of total CO2 emissions from the thermal energy spent for aggregates and bitumen at the asphalt plant, based on a linear relationship between heating temperature of raw materials and related CO2 emissions.

These results are comparable with the decrease of 2.9 kg CO2 per ton of asphalt concrete recorded by West et al. [50] for a difference in production temperature of 17 °C between HMA (20.9 kg CO2 per ton) and WMA produced with a chemical additive (18 kg CO2 per ton).

5.4. Electricity consumption and emissions of CO2 in the mixing phase

WMA and HMA differ in the duration of the mixing phase, with WMA having 4 s longer mixing time than HMA. The electricity consumption for the mixing of 1 ton of HMA and WMA was calculated through Eq. (12) and resulted in 0.109 and 0.126 kWh, respectively. Then, Eq. (15) was used for the calculation of the emissions of CO2, which provided values equal to 0.027 and 0.031 kg, respectively, for HMA and WMA. This results in about 15% higher electricity consumption and related CO2 emissions for the WMA compared to the HMA mixing phase.

5.5. Total CO2 emissions for aggregates and bitumen heating and for mixing phase

Table 7 summarizes the CO2 emissions related to the three production phases (i.e., drying/heating aggregates, heating bitumen, and

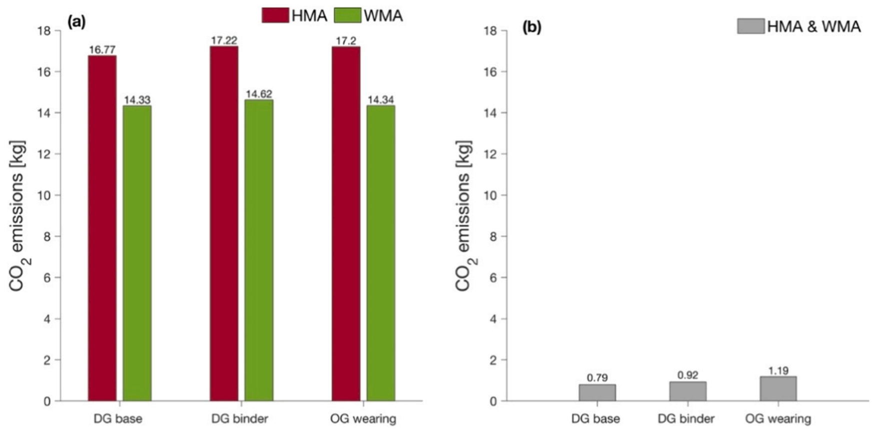

Fig. 6. Emissions of CO2 from consumption of (a) fuel oil for drying/heating aggregates, and (b) liquified petroleum gas for heating bitumen to produce 1 ton of different mixture types with different production technologies.

Table 7
CO2 emissions for the three production phases between different mixture types and production technologies.

Production phase	CO2 emissions [kg]								
	DG_base			DG_binder			OG_wearing		
	WMA	HMA	Δ	WMA	HMA	Δ	WMA	HMA	Δ
Drying/ heating aggregates	14.33	16.77	-2.45	14.62	17.22	-2.61	14.34	17.20	-2.86
Heating bitumen	0.79	0.79	—	0.92	0.92	—	1.19	1.19	—
Mixing	0.031	0.027	0.004	0.031	0.027	0.004	0.031	0.027	0.004
Total	15.15	17.59	**-2.44**	15.57	18.17	**-2.60**	15.56	18.42	**-2.86**

mixing) described in the previous sections as well as the total CO2 emission and the differences (Δ) between WMA and HMA production technology.

For both HMA and WMA, the highest share of CO2 emissions is for drying/heating aggregates, followed by heating bitumen and mixing phase, confirming that the aggregate heating is the most penalizing phase in terms of CO2 emissions and that the difference in mixing duration of WMA (26 s) with respect to HMA (30 s) can be considered negligible in terms of CO2 emissions.

The reduction in production temperature of 40 °C between WMA and HMA results in an absolute average reduction of CO2 emissions of about 2.63 kg per ton (Table 7) of mixture produced (DG_base, DG_binder or OG_wearing). Considering that the average annual asphalt concrete production of the considered asphalt plant is equal to about 60,000 tons, a shift from HMA to WMA production would lead to a reduction in CO2 emissions of 158 tons per year.

6. Airborne pollutants (NOx, VOCs, CO, particulate matter, and SOx) emitted per ton of HMA and WMA during drying/heating aggregates

Together with CO2 emissions studied so far, airborne pollutant emissions should be also considered. Besides their direct harmful effects on human health and ecosystems, carbon monoxide, non-methane VOCs, and nitrous oxides are precursors of tropospheric ozone and secondary ultrafine PM with further implications on the ecosphere ([16] and [11]). Specifically, Clappier et al. [11] have pointed out that the relationship between ambient level of secondary PM2.5 and emission of its precursors (e.g., SO2 and NOx) vary with seasons and areas of Europe. Moreover, Clappier et al. [11] observed that measures aimed at reducing secondary PM2.5 levels should consider that the effect could be nonlinear for NOx emissions. According to the annual report on air quality in Europe by the European Environment Agency [17], in Italy about 68,000 premature deaths were attributable to exposure to PM2.5, NO2, and O3 in 2020. The attributable number of premature deaths is the highest for exposure to PM2.5, about five and ten times the adverse health outcomes due to exposure to NO2 and O3, respectively. Differently, in Italy, annual SO2 and CO emissions showed a decreasing trend, with 63 and 39% lower values in 2020 compared to 2010 [44]. Moreover, in the decade 2010–2020 Italy recorded annual SO2 emissions far below the SO2-ceiling imposed to the Member States by the directive on national emission reduction commitments [45]. Therefore, it can be assumed that emissions of SOx and CO do not represent today a core environmental issue in Italy.

Eq. (16) was employed for calculating the emission factors shown in Fig. 7, where the results for different airborne pollutants (CO, SOx, NOx, VOCs, and PM) are reported by starting from the measurements performed in the work of Stimilli et al. [41].

The drying/heating phases of aggregates for WMA lead to about 18, 22, and 35% lower emissions of PM, NOx, and VOCs, respectively, compared to HMA. This agrees with the results obtained by Sol-Snchez at al. [39] and West et al. [50], even if different reduction percentages were obtained, mainly due to different mixture production procedures and measurement conditions.

On the contrary, Fig. 7 shows that emissions of CO and SOx for drying/heating aggregates were 22% and 1% higher, respectively, for WMA compared to HMA. Similarly, this outcome agrees with the results obtained by Sol-Sánchez et al. [39], who recorded a 3% increase in CO emissions with WMA at 140 °C compared to HMA at 176 °C. The results also agree with West et al. [50], who observed a 49% increase in CO emission during WMA production at 132 °C compared to HMA production at 149 °C. This increase in CO emissions can be explained by considering that these emissions are strictly related to the burner setting at the asphalt plant ([12] and [4]), allowing also to explain the differences in CO emissions between the different studies. Indeed, moving production from HMA to WMA would require extensive burner tuning depending on the production technology and type of fuel. However, in this investigation, the WMA production involved only about 1500 tons of asphalt mixtures making time consuming and uneconomical the modification of the burner setting, which was set for routine HMA

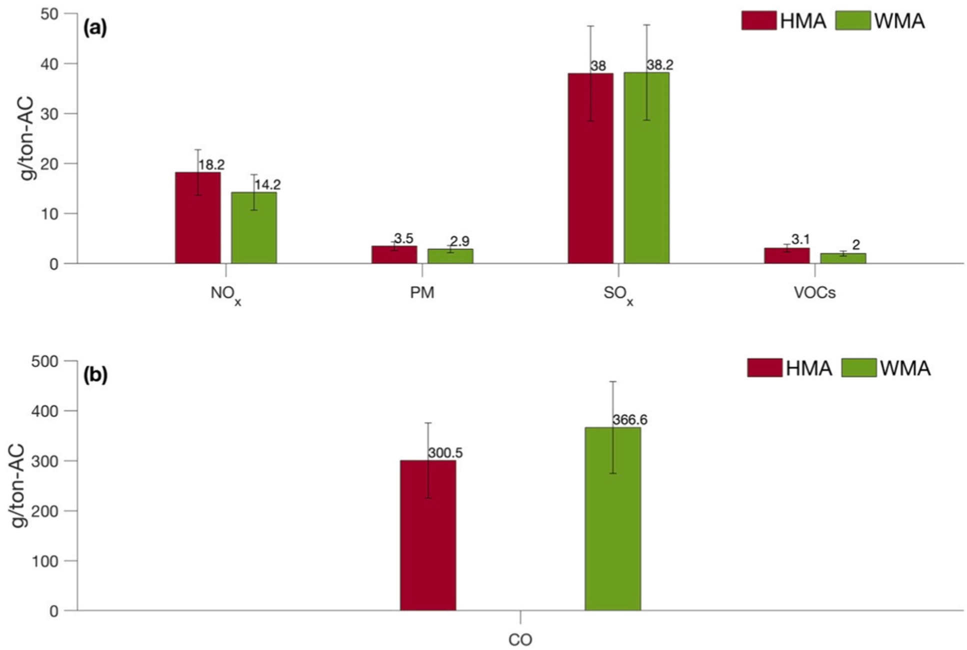

Fig. 7. Comparisons between emissions of (a) NOx, SOx, volatile organic compounds (VOCs), particulate matter (PM), and (b) CO per ton of HMA and WMA for heating/drying the aggregates. Own elaboration based on data from Stimilli et al. [41]. AC–asphalt concrete.

production. For this reason, in this study, the increase in CO emissions during WMA production was expected. The asphalt plant operator is aware that it is necessary to modify the burner setting if the WMA production becomes continuous.

However, as mentioned above, in Italy, emissions of SOx and CO today represent a less important environmental issue when compared with other pollutant emissions.

7. Conclusions

A case study concerning the reconstruction of a full-scale trial section in an Italian motorway by employing hot and warm bituminous mixtures prepared with a polymer modified bitumen and different WMA chemical additives was presented. Calculations and analyses were performed considering three production phases (i.e., drying/heating of aggregates, heating of bitumen, and mixing) during which the production technology (HMA and WMA) and the mixture type (for base, binder and porous wearing course) differ in terms of temperatures involved, mixing duration, and quantity of virgin materials employed. For comparing WMA and HMA production, energy and fuel consumption as well as emissions of CO2 were calculated, whereas airborne pollutants (i.e., CO, VOCs, SOx, PM, and NOx) were measured at the asphalt plant.

For each mixture type, a reduction of 40 °C in mixing temperature (130°C for WMA vs. 170°C for HMA) implies a reduction of about 15% of thermal energy for drying/heating aggregates. This corresponds to an analogous reduction in fuel oil consumption and CO2 emissions. Drying/heating aggregates for WMA lead to about 18, 22, and 35% lower emissions of PM, NOx, and VOCs, respectively, compared to HMA. On the contrary, emissions of other airborne pollutants were comparable (1% for SOx) or higher (22% for CO) for WMA compared to HMA. However, the increase of emissions mostly depends on the unadjusted burner setting that should be optimized for WMA production.

For both HMA and WMA, the highest share of CO2 emissions is for drying/heating aggregates, followed by heating bitumen and finally for the mixing phase. Specifically, the difference in emissions of CO2 due to the different mixing duration between WMA (30 s) and HMA (26 s) can be considered negligible compared to the difference in emissions due to the drying drum phase.

For the asphalt plant investigated, a shift to production of recycled bituminous warm mixtures with chemical additives would correspond to energy and fuel savings with positive implications in emissions.

It is important to point out that data on parameters that play a significant role in energy efficiency and emissions at asphalt plants are limited, despite the interest in improving the environmental footprint of the road construction sector. Future insights could come from measurement campaigns of key parameters (e.g., moisture content of aggregates, rate of production, and fuel consumption) for different mixing technologies and production phases in asphalt plants. This study also highlights the need to extend the analysis of energy and environmental performance to other asphalt plants using different production technologies, other types of fuel, and optimized burner settings.

CRediT authorship contribution statement

G. Ferrotti: Writing – review & editing, Validation, Supervision, Project administration, Investigation, Data curation. **E. Mancinelli**: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Passerini**: Writing – review & editing, Supervision, Project administrationg. **F. Canestrari**: Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The activities presented in this paper were sponsored by AMPLIA Infrastructures (Italy), which gave both financial and technical support within the framework of the Extreme Recycling of Asphalt (ERA) project. The results and opinions presented are those of the authors.

References

[1] A. Almeida-Costa, A. Benta, Economic and environmental impact study of warm mix asphalt compared to hot mix asphalt, J. Clean. Prod. *112* (2016) 2308–2317, https://doi.org/10.1016/j.jclepro.2015.10.077.

[2] I. Androjić, Z.D. Alduk, S. Dimter, T. Rukavina, Analysis of impact of aggregate moisture content on energy demand during the production of hot mix asphalt (HMA), J. Clean. Prod. *244* (2020) 118868, https://doi.org/10.1016/j.jclepro.2019.118868.

[3] B.W. Ang, T.F. Fwa, T.T. Ng, Analysis of process energy use of asphalt-mixing plants, Energy *18* (7) (1993) 769–777.

[4] J. Anthonissen, J. Braet, Review and environmental impact assessment of green technologies for base courses in bituminous pavements, Environ. Impact Assess. Rev. *60* (2016) 139–147, https://doi.org/10.1016/j.eiar.2016.04.005.

[5] D.E.G. Bizarro, Z. Steinmann, I. Nieuwenhuijse, E. Keijzer, M. Hauck, Potential carbon footprint reduction for reclaimed asphalt pavement innovations: Lca methodology, best available technology, and near-future reduction potential, Sustainability *13* (3) (2021) 1382, https://doi.org/10.3390/su13031382.

[6] Bueche N., Dumont A.G. Energy in warm mix asphalt. In: Proceedings of the 5th Eurasphalt & Eurobitume Congress, Istanbul, Turkey; 2012.

[7] T.A. Calabi-Floody, A.G. Valdés-Vidal, E. Sanchez-Alonso, A.L. Mardones-Parra, Evaluation of gas emissions, energy consumption and production costs of warm mix asphalt (WMA) involving natural zeolite and reclaimed asphalt pavement (RAP), Sustainability 12 (2020) 6410, https://doi.org/10.3390/su12166410.

[8] P. Caputo, A.A. Abe, V. Loise, M. Porto, P. Calandra, R. Angelico, C. Oliviero Rossi, The role of additives in warm mix asphalt technology: an insight into their mechanisms of improving an emerging technology, Nanomaterials 10 (6) (2020) 1202, https://doi.org/10.3390/nano10061202.

[9] G. Cheraghian, A.C. Falchetto, Z. You, S. Chen, Y.S. Kim, J. Westerhoff, K.H. Moon, M.P. Wistuba, Warm mix asphalt technology: an up to date review, J. Clean. Prod. *268* (2020) 122128, https://doi.org/10.1016/j.jclepro.2020.122128.

[10] A. Chlebnikovas, E. Marčiulaitienė, O. Šernas, J. Škultecké, T. Januševičius, Research on air pollutants and odour emissions from paving hot-mix asphalt with end-of-life tyre rubber, Environ. Int. (2023) 108281, https://doi.org/10.1016/j.envint.2023.108281.

[11] A. Clappier, P. Thunis, M. Beekmann, J.P. Putaud, A. de Meij, Impact of SOx, NOx and NH3 emission reductions on PM2. 5 concentrations across Europe: Hints for future measure development, Environ. Int. *156* (2021) 106699, https://doi.org/10.1016/j.envint.2021.106699.

[12] d'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowsert, J., Harman, T., Jamshidi, M., Jones, W., Newcomb, D. and Prowell, B., 2008. Warm-mix asphalt: European practice (No. FHWA-PL-08-007). United States. Federal Highway Administration. Office of International Programs.

[13] European Asphalt Pavement Association (EAPA). 2021. Asphalt in figures–Provisional Figures 2021. ⟨https://eapa.org/asphalt-in-figures/⟩.

[15] European Commission, Directorate-General for Climate Action, The EU emissions trading system (EU ETS), Publications Office, 2013, ⟨https://data.europa.eu/doi/10.2834/55480⟩.

[16] European Environment Agency. 2014. Emissions of ozone precursors. Available online: IND-23-enEuropean Environment Agency (EEA). 2022. Italy – air pollution country fact sheet. Available online:⟨https://www.eea.europa.eu/themes/air/country-fact-sheets/2022-country-fact-sheets/italy-air-pollution-country⟩ (accessed on 27 April 2023).

[17] European Environment Agency. 2022. Air quality in Europe 2022. Report no. 05/2022. doi: 10.2800/488115.

[18] M.I. Giani, G. Dotelli, N. Brandini, L. Zampori, Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling, Resour. Conserv. Recycl. *104* (2015) 224–238, https://doi.org/10.1016/j.resconrec.2015.08.006.

[19] M. Guo, H. Liu, Y. Jiao, L. Mo, Y. Tan, D. Wang, M. Liang, Effect of WMA-RAP technology on pavement performance of asphalt mixture: a state-of-the-art review, J. Clean. Prod. 266 (2020) 121704.

[20] M.O. Hamzah, A. Jamshidi, Z. Shahadan, Evaluation of the potential of Sasobit® to reduce required heat energy and CO2 emission in the asphalt industry, J. Clean. Prod. *18* (18) (2010) 1859–1865, https://doi.org/10.1016/j.jclepro.2010.08.002.

[21] F. Huchet, L. Le Guen, P. Richard, M. Piton, B. Cazacliu, P. Semelle, J. Matheus, H. Riche, P. Tamagny, Influence of asphalt composition upon the thermodynamics performance of a mixing plant, Road. Mater. Pavement Des. *19* (1) (2018) 104–119, https://doi.org/10.1080/14680629.2016.1249018.

[22] L.P. Ingrassia, S. Spadoni, G. Ferrotti, A. Virgili, F. Canestrari, Prediction of the long-term performance of an existing warm recycled motorway pavement, Materials 16 (3) (2023) 1005.

[23] Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)., 2022. Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico. ISPRA, Rapporti 363/2022. Available online: ⟨https://www.isprambiente.gov.it/files2022/pubblicazioni/rapporti/r363-2022.pdf⟩.

[24] K. Li, X. Yan, J. Pu, Y. Wang, Y. Chen, K. Fang, J. Hu, Y. Yang, Quantitative evaluation on the energy saving and emission reduction characteristics of warm mix asphalt mixtures, Constr. Build. Mater. *407* (2023) 133465, https://doi.org/10.1016/j.conbuildmat.2023.133465.

[25] E. Mancinelli, F. Canestrari, A. Graziani, U. Rizza, G. Passerini, Sustainable performances of small to medium-sized airports in the adriatic region, Sustainability 13 (2021) 13156, https://doi.org/10.3390/su132313156.

[26] T. Mattinzioli, M. Sol-Sanchez, A.J. del Barco Carrion, F. Moreno-Navarro, Carmen del, M. Rubio-Gamez, G. Martinez, Analysis of the GHG savings and cost-effectiveness of asphalt pavement climate mitigation strategies, J. Clean. Prod.. *320* (2021) 128768, https://doi.org/10.1016/j.jclepro.2021.128768.

[27] Ministero dell'ambiente e della sicurezza energetica (MASE). 2022. EU ETS – Italia - Tabella coefficienti standard nazionali 2019-2021. Available online: ⟨https://www.ets.minambiente.it/News#272-pubblicazione-parametri-standard-nazionali-anno-2022⟩.

[28] L.N. Mohammad, M.M. Hassan, B. Vallabhu, M.S. Kabir, Louisiana's experience with WMA technologies: mechanistic, environmental, and economic analysis, J. Mater. Civ. Eng. 27 (6) (2015) 04014185, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001143.

[29] J. Oner, B. Sengoz, Utilization of recycled asphalt concrete with warm mix asphalt and cost-benefit analysis, PLoS One *10* (1) (2015) e116180. DOI:10.1371/journal.pone.0116180.

[30] R.S. Paranhos, C.O. Petter, Multivariate data analysis applied in hot-mix asphalt plants, Resour. Conserve Recycl. *73* (2013) 1–10, https://doi.org/10.1016/j.resconrec.2013.01.009.

[31] B. Peng, C. Cai, G. Yin, W. Li, Y. Zhan, Evaluation system for CO2 emission of hot asphalt mixture, J. Traffic Transp. Eng. (Engl. Ed.) *2* (2) (2015) 116–124, https://doi.org/10.1016/j.jtte.2015.02.005.

[32] A.M. Rodríguez-Alloza, A. Malik, M. Lenzen, J. Gallego, Hybrid input–output life cycle assessment of warm mix asphalt mixtures, J. Clean. Prod.. *90* (2015) 171–182, https://doi.org/10.1016/j.jclepro.2014.11.035.

[33] A. Romier, M. Audeon, J. David, Y. Martineau, F. Olard, Low-energy asphalt with performance of hot-mix asphalt, Transp. Res. Rec. *1962* (1) (2006) 101–112, https://doi.org/10.1177/0361198106196200112.

[34] J. Santos, S. Bressi, V. Cerezo, D.L. Presti, M. Dauvergne, Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: a comparative analysis, Resour. Conserv. Recycl. *138* (2018) 283–297, https://doi.org/10.1016/j.resconrec.2018.07.012.

[35] J. Santos, G. Flintsch, A. Ferreira, Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability, Resour. Conserv. Recycl. *116* (2017) 15–31, https://doi.org/10.1016/j.resconrec.2016.08.0.

[37] M.S. Siverio Lima, M. Hajibabaei, S. Hesarkazzazi, R. Sitzenfrei, A. Buttgereit, C. Queiroz, V. Haritonovs, F. Gschösser, Determining the environmental potentials of urban pavements by applying the cradle-to-cradle LCA approach for a road network of a midscale German city, Sustainability *13* (2021) 12487, https://doi.org/10.3390/su132212487.

[38] M.S. Siverio Lima, C. Makoundou, C. Sangiorgi, F. Gschösser, Life cycle assessment of innovative asphalt mixtures made with crumb rubber for impact-absorbing pavements, Sustainability 14 (2022) 14798, https://doi.org/10.3390/su142214798.

[39] M. Sol-Sánchez, F. Moreno-Navarro, G. García-Travé, M.C. Rubio-Gámez, Analysing industrial manufacturing in-plant and in-service performance of asphalt mixtures cleaner technologies, J. Clean. R. Prod. *121* (2016) 56–63, https://doi.org/10.1016/j.jclepro.2016.02.046.

[40] S. Spadoni, L.P. Ingrassia, E. Mariani, F. Cardone, F. Canestrari, Long-term performance assessment of a warm recycled motorway pavement, Case Stud. Const. Mater. 17 (2022) e01451, https://doi.org/10.1016/j.cscm.2022.e01451.

[41] A. Stimilli, F. Frigio, F. Canestrari, S. Sciolette, In-plant production of warm recycled mixtures produced with SBS modified bitumen: a case study. In Proceedings of the AIIT International Congress on, Transp. Infrastruct. Syst., TIS (2017) 143–151.

[42] A. Stimilli, A. Virgili, F. Canestrari, Warm recycling of flexible pavements: effectiveness of Warm Mix Asphalt additives on modified bitumen and mixture performance, J. Clean. Prod. *156* (2017) 911–922, https://doi.org/10.1016/j.jclepro.2017.03.235.

[43] M. Sukhija, N. Saboo, A. Pani, Economic and environmental aspects of warm mix asphalt mixtures: A comparative analysis, Transp. Res. Part D: Transp. Environ. *109* (2022) 103355, https://doi.org/10.1016/j.trd.2022.103355.

[44] Taurino, E., Bernetti, A., Caputo, A., Cordella, M., De Laurentis, R., D'Elia, I. et al. 2022. Italian Emission Inventory 1990-2020. Informative Inventory Report 2022. Rapporti 361/2022. Available online: ⟨https://www.isprambiente.gov.it/files2022/pubblicazioni/rapporti/iir_2022_italy-stampa-rev.pdf⟩ (accessed on 27 April 2023).

[45] The European Parliament and the Council. 2016. Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC (Text with EEA relevance)⟨http://data.europa.eu/eli/dir/2016/2284/oj⟩.

[46] L.P. Thives, E. Ghisi, Asphalt mixtures emission and energy consumption: a review, Renew. Sust. Energ. Rev. *72* (2017) 473–484, https://doi.org/10.1016/j.rser.2017.01.087.

[47] R. Vidal, E. Moliner, G. Martínez, M.C. Rubio, Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement, Resour. Conserv. Recycl. *74* (2013) 101–114, https://doi.org/10.1016/j.resconrec.2013.02.018.

[48] J.M. Wallace, P.V. Hobbs. Atmospheric Science: an Introductory Survey, Elsevier, 2006. Vol. 92.

[49] F. Wang, I. Hoff, F. Yang, S. Wu, J. Xie, N. Li, L. Zhang, Comparative assessments for environmental impacts from three advanced asphalt pavement construction

cases, J. Clean. Prod. *297* (2021) 126659, https://doi.org/10.1016/j.jclepro.2021.126659.

[50] R. West, C. Rodezno, G. Julian, B. Prowell, B. Frank, L.V. Osborn, T. Kriech, Field Performance of Warm Mix Asphalt Technologies (No. Project 9-47A), Washington, DC: The National Academies Press, 2014, https://doi.org/10.17226/22272.

[51] N.S.A. Yaro, M.H. Sutanto, L. Baloo, N.Z. Habib, A. Usman, A.K. Yousafzai, A. Ahmad, A.H. Birniwa, A.H. Jagaba, A. Noor, A comprehensive overview of the utilization of recycled waste materials and technologies in asphalt pavements: towards environmental and sustainable low-carbon roads, Processes *11* (2023) 2095, https://doi.org/10.3390/pr11072095.