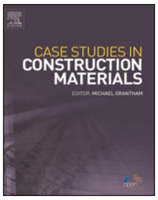
Case Studies in Construction Materials 16 (2022) e00987

Contents lists available at ScienceDirect

Case Studies in Construction Materials

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



Case study

Economic and environmental impacts of utilizing lower production temperatures for different bitumen samples in a batch plant

Ali Almusawi [a,*], Burak Sengoz [b], Derya Kaya Ozdemir [b], Ali Topal [b]

[a] Çankaya University, Department of Civil Engineering, Ankara, Turkey
[b] Dokuz Eylul University, Department of Civil Engineering, Izmir, Turkey

ARTICLE INFO

Keywords:
Asphalt
Batch type plant
Carbon dioxide emissions
Hot mix asphalt
Energy consumption
Warm mix asphalt
Polymer modified bitumen

ABSTRACT

The utilization of hot mix asphalt (HMA) for road construction necessitates high temperatures during mixing bitumen and aggregate at asphalt plant. The required (mixing) production temperature is calculated by the standard method (ASTM 2493). The application of this method for polymer modified bitumen (PMB) and warm mix asphalt (WMA) have tendency of higher temperatures. Therefore, some alternative methods suggested by literatures for the determination of production temperature for PMB and WMA have been implemented aiming to determine lower temperatures than the standard method (ASTM 2493). Moreover, the economic impacts of the determined production temperatures through different models are evaluated by the estimation of energy consumption in terms of electricity and natural gas costs for the batch type asphalt plants. Besides, the possible environmental effects are calculated by considering the carbon dioxide emissions. The results of this study have shown that the reduction in production temperatures led to a significant decrease in the total construction cost of each type of asphalt and a significant reduction in the estimated carbon dioxide emission. The results of this study can be used as a reference point for the estimation of both economic and environmental impacts of utilizing lower production temperatures for different bitumen samples.

1. Introduction

Flexible pavements, which are also generally known as hot mix asphalt (HMA), are the most common type of pavements over the world. This is due to their low initial construction cost, surface smoothness, load distribution characteristics, etc. [1]. HMA is usually constructed of bitumen and aggregates which should be heated at elevated temperatures before the production of the mix at the asphalt mixing plant, the required mixing temperature is generally determined through a standard method (ASTM D2493). The standard method was developed based on unmodified bitumen behavior. Thus, the application of this method on other bitumen types such as polymer modified bitumen and warm mix asphalt is not proper since the behavior of such materials is not taking into consideration [2–11]. Consequently, the determined temperatures for such materials are excessively high and the implementation of those temperatures will create a higher energy consumption which will harm the environment as well as increase the total cost of the asphalt production.

---

[*] Corresponding author.
E-mail address: ali.almusawi@cankaya.edu.tr (A. Almusawi).

https://doi.org/10.1016/j.cscm.2022.e00987
Received 26 December 2021; Received in revised form 10 February 2022; Accepted 25 February 2022

The energy consumption during the HMA manufacturing process affected by a couple of constraints such as the moisture level in the mineral, the interruptions during the manufacturing process, and the production temperature of the asphalt mixture. Ang, Fwa, and Ng (1993) observed that a 3% decrease in the mixture's moisture level resulted in a 55–60% energy savings [12]. In another study carried out by Young (2008), considered the influence of the discontinuity in the production of asphalt mixture, and he exhibited that any interruptions may create a fuel expenditure between 20% and 35%. In addition, the temperature during the manufacturing of HMA is an important factor in energy consumption [13]. Jenny (2009) showed that the reduction in the production temperature from 180 °C to 115 °C during the manufacture of an asphalt mixture develops a reduction in fuel consumption for 1.5 kg/t of produced asphalt mixture [14]. Therefore, in the perspective of energy consumption, the usage of bituminous material that requires lower production temperature such as the warm mix asphalt (WMA) technology is a good alternative for the HMA since it requires lower production temperature [15,16]. However, in order to satisfy the development in the traffic demand, the utilization of different polymer types into the bitumen is considered as a practical solution. Nevertheless, using polymer modified bitumen (PMB) necessitates higher production temperatures, which may generate harmful atmospheric emissions than the base (unmodified) bitumen [17–19].

On the other hand, energy consumption is also influenced by the type of plant to be used. Generally speaking, the energy consumption of the batch type is higher than the drum mix type, in which the mineral materials are dried, heated, and mixed in the same drum. However, batch type is currently more popular due to its versatility, handling, and better quality of production [12].

Since the impact of utilizing lower mixing and compaction temperatures on the performance of asphalt concrete samples such as Marshall characteristics and Indirect Tensile Test was investigated by some recent studies [20,21]. Thus, in this paper, the aim is to highlight a different perspective by taking into consideration the estimation of both economic and environmental impacts utilizing lower production temperatures for different bitumen samples. Several proposed methods (High Shear Rate, Zero Shear Viscosity, and Steady Shear Flow method) have been implemented on the bitumen samples modified with different polymers and WMA additives. The economic impacts of the determined production temperatures through different models have been evaluated by the estimation of energy consumption in terms of electricity and natural gas costs for the asphalt batch type plant. Moreover, the expected environmental influences have been considered by estimating of the carbon dioxide emissions.

2. Materials

The base bitumen with 50/70 and 160/220 penetration grades were obtained from Dere Group Inc./ Izmir/ Turkey. In order to identify the physical properties of the base bitumen, traditional test methods such as penetration test (ASTM D5-06), softening point test (ASTM D36-95), Rolling thin film oven test (RTFOT) (ASTM D2872-12), penetration and softening point after RTFOT, etc. were conducted and the results are presented in Table 1.

Two types of polymers, SBS Kraton® D1101 as elastomer and Elvaloy® 4170 as plastomer together with two types of WMA additive, Sasobit® as organic and Rediset® as chemical, were utilized to prepare modified bitumen. The production details regarding the percentage of each additive and mixing conditions in terms of mixing temperature, duration, and shearing rates are given in Table 2.

The cost of the asphalt is also determined including the raw material cost, the heating cost, and the different utilized additives cost to give a better clue about the initial cost as presented in Table 3. However, the analysis in this study considered only the influence of the production temperature regardless of the asphalt production cost.

3. Methods

This study aims to investigate the possible economic and environmental influences of different bitumen samples at different production temperatures for the batch plant. Consequently, the mixing temperatures of bitumen samples were determined using different methods as the first stage. The second stage is considering the electricity and natural gas consumption costs in order to cover the economic perspective. Finally, from the environmental perspective, the carbon dioxide emission is estimated using a model correlate the mixing temperature with carbon emissions. Detailed methodology used in this study is shown in Fig. 1.

Table 1
Base bitumen properties.

Test	Specification	Results		Specification limits	
		50/70	160/220	50/70	160/220
Penetration (25 °C; 0.1 mm)	ASTM D5	65	190	50–70	160–220
Softening point (°C)	ASTM D36	51	41	46–54	35–43
Penetration index (PI)	–	0.35	0.123	–	
Rolling thin film oven test (RTFOT)	ASTM D2872-12				
Change of mass (%)	–	0.160	0.94	0.5 (max.)	0.5 (max.)
Penetration (25 °C; 0.1 mm)	ASTM D5	53	97	50 (min.)	50 (min.)
Retained penetration (%)	ASTM D5	82	51	50 (min.)	50 (min.)
Softening point after RTFOT (°C)	ASTM D36	58	50	48 (min.)	48 (min.)

Table 2
Production detailed regarding the additives and modifications.

Modifier Type		Percentage (%)	Production Conditions		
			Mixing Temperature (°C)	Mixing Duration (min)	Shearing Rate (rpm)
Polymer	SBS Kraton® D1101	5	180 ± 5	120	2000
	Elvaloy® 4170	1.5	190	120	200
WMA Additive	Organic (Sasobit®)	3	120	10	1000
	Chemical (Rediset®)	3	150	15	1000

Table 3
Production cost different asphalt samples.

	Hot Mix Asphalt	Warm Mix Asphalt		PMB	
		Organic WMA Additive	Chemical WMA Additive	SBS	Elvaloy
Total aggregate cost (USD/ton)	8.58	8.58	8.58	8.58	
Total bitumen cost (TRY/ton)	26.455	20.306	20.592	22.1656	22.022
Heating of the bitumen (TRY/ton)	1.532	2.245	1.788	1.42	1.40
Cost of WMA additive (TRY/ton)	–	4.00	16.252.33	–	–
Cost of Polymer (TRY/ton)	–	–		2.90	2.58

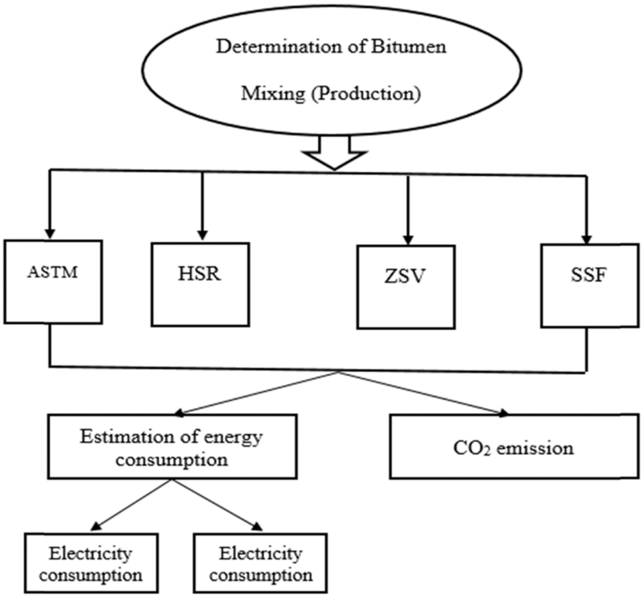


Fig. 1. Flow chart for the test method.

3.1. *Determination of bitumen mixing (production) temperatures*

ASTM 2493 is the most common method used to determine the mixing and compaction temperatures for bituminous materials. In the standardized method (ASTM D2493), the viscosity values are obtained at a constant shear rate (6.8 1/s) and two different temperatures (135 °C and 165 °C). The measured viscosity values are plotted against the temperature. The viscosity ranges to determine the mixing and compaction temperatures should be 0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s, respectively [4].

Over the past few decades, there are numerous trials by many researchers to define a more realistic procedure for obtaining the mixing and compaction temperatures for modified bitumen samples, instead of ASTM D 2493 method. One of the earlier trails was developed by Solaimanian et al. (2000). In this method, they calculated the shear rate inside the Superpave Gyratory Compactor of 487 s-1, which was rounded to 490 s-1, and defined that mixing and compaction temperatures should be determined by considering 490 s-1 instead of 6.8 s-1 with the same viscosity ranges (0.17 ± 0.02 Pa. s and 0.28 ± 0.03 Pa. s). This method is designated as the High Shear Rate Viscosity (original), HSR-O [22]. In a more recent study, they stated that current viscosity ranges fail to meet the standard method assumption and should be increased to 0.275 ± 0.03 Pa. s and 0.550 ± 0.06 Pa.s. This method is designated as the High Shear Rate Viscosity (evolution), HSR-E [23].

Another attempt suggested the Zero Shear Viscosity (ZSV) measurements to be used for determining the mixing and compaction temperatures of modified bitumen. The hypothesis of this method is based on the measurement of the modified bitumen viscosity supposed to be conducted at a lower shear rate than the suggested by the traditional method (6.8 1/s). In order to calculate the ZSV, it is proposed that the Cross Williamson model be used. The mixing and compaction temperatures corresponding to 3 ± 0.3 Pa s and 6 ± 0.6 Pa s, respectively [24].

Some other researchers proposed the utilization of the Dynamic Shear Rheometer in order to measure the bitumen samples at more sensitive machine especially the modified samples. The steady Shear Flow (SSF) method is one of the first trails that included the behavior of the bitumen at different test conditions. This method is based on the shear dependency behavior of the bitumen sample [25]. Based on the recommended procedure, the viscosity values are measured using the Dynamic Shear Rheometer (DSR) at different shear stresses (0.3–500 Pa). The test is performed over a range of temperatures 76 °C, 82 °C, and 88 °C. The measured viscosity values at 500 Pa, where the viscosity value reaches the steady-state condition, are plotted using a log viscosity versus log temperature chart to obtain the mixing and compaction temperatures through using the suggested viscosity limits 0.17 ± 0.02 Pa s and 0.35 ± 0.03 Pa s, respectively.

In this study, the above mentioned five methods (ASTM D2493, HSR-O, HSR-E, ZSV, and SSF) are used to determine the mixing and compaction temperatures. The summary of these methods is illustrated in Table 4.

3.2. *Estimation of energy consumption*

There are various parameters taken into account during the production of asphalt in plants however within the scope of the study, comparisons have been made by considering the mixing (production) temperature values determined with different models. The impact of the variation of the determined mixing temperature for the bitumen samples produced with 50/70 and 160/220 penetration grade and different additives on the natural gas and electricity consumption during the asphalt production is discussed at batch type pant. The technical specification of the batch type asphalt plant utilized in this study is described in Table 5. Since there is no standard related to this concept, evaluations will be made on the results based on the previous literature studies. The economic analysis was conducted using the U.S. Dollar.

3.2.1. *Electricity consumption*

For batch type plants, the electricity consumption is calculated as of 3.24 kWh/ton at a temperature level of 160–165 °C with an annual production of 100,000 tons [26]. Bražiūnas and Sivilevičius (2014) investigated the dependency of electrical consumption on the utilized production temperature in batch type asphalt plants [27]. They suggested that every 5 °C temperature variation in the batch type asphalt plant creates an 11% change in electricity consumption. In light of these findings, the current pricing is calculated for the production of 100.000 tons of asphalt for variable production temperatures (Table 6). As of January 2020, 1kWh electricity usage has been taken as 0,9523 Turkish Lira (TRY) in cost calculation for industrial usage (1 TRY currency equals to 0.143 USD in May 2020).

3.2.2. *Natural gas consumption*

Androjić and Alduk (2016) carried out a model-based study on the influence of various factors on the change of natural gas consumption in the batch type asphalt plant [28]. The study aimed to create models that correlate between the energy consumed at the batch type asphalt plant with the production temperature, the moisture in the aggregate particles, and the hourly capacity. The capacity of the dryer is specified according to a certain amount of moisture (usually 5%). If the moisture content of the aggregate is above the given value, the amount of aggregate directed to the dryer must be reduced in order to dry and heat the aggregate well. Therefore,

Table 4
Summary of the utilized methods.

Method	Viscosity limits for mixing temperature (Pa s) (Production)	Viscosity limits for compaction temperature (Pa s)	Proposed Equipment	Reference
ASTM D2494	0.17 ± 0.02	0.28 ± 0.03	Brookfield	[4]
High Shear Rate-Original (HSR-O)	0.17 ± 0.02	0.28 ± 0.03	Brookfield	[15]
High Shear Rate-Evolution (HSR-E)	0.275 ± 0.03	0.550 ± 0.06	Brookfield	[16]
Zero Shear Viscosity (ZSV)	3.0	6.0	Brookfield	[17]
Steady Shear Flow (SSF)	0.17 ± 0.02	0.35 ± 0.03	DSR	[18]

Table 5
Technical specification of the batch type asphalt plant.

Mixture type	Asphalt concrete
Draying duration (second)	300
Capacity (ton/h)	160
Annual production (ton)	100 000
Electricity (kWh) (3.24 kWh/ton)	324 000
Other fuels, diesel, (L) (0.9 L/ton)	90 000
Heating and drying, natural gas (m^3)	1 060 547
Mixer capacity (kg)	2 000 – 2 250
Transport of materials to the planet-distance	10
-Aggregate, capacity > 17 ton (km)	100
-Bitumen, capacity > 3.5–33 ton (km)	

Table 6
Energy Consumption corresponding to different mixing (production) temperatures for batch type asphalt plant usage.

Temperature (°C)	Energy Consumption (kWh/ton)	Energy Consumption Cost (USD/ton)	Annual Energy Consumption Cost (for 100 000 ton)-USD
120–125	0.79	0.11	10725
125–130	0.89	0.12	12012
130–135	1.58	0.21	21450
135–140	1.78	0.24	24167
140–145	2.00	0.27	27313
145–150	2.26	0.31	30745
150–155	2.55	0.35	34749
155–160	2.87	0.39	39182
160–165	3.24	0.44	44187
165–170	3.61	0.49	49049
170–175	4.01	0.55	54626
175–180	4.47	0.61	60918
180–185	4.89	0.68	67782
185–190	5.54	0.75	75361

this reduces the production capacity. Apart from this, the temperature of the mixture to be produced and the type of aggregate also affect the performance. Briefly, the most important factor affecting the performance of the plant; is the drying and heating process.

The experiments involve the manufacture of 88 079 ton of hot mix asphalt of dense and gap gradation on a cyclic asphalt plant in the Republic of Croatia. The temperature of the manufactured asphalt mixture was determined utilizing around 67 753 samples throughout the entire manufacture period. The approximate densities of the manufactured asphalt mixtures are between 2550 and 2700 kg/m3 with an air void content in the limit of 2.5–7%. During manufacture, eruptive and dolomite stone aggregates were utilized, and polymer modified bitumen. The average daily temperatures at the asphalt plant ranged from 158° to 184°C during the test. The production temperature is correlated with energy consumption in terms of natural gas. Based on the analysis results, a regression function between the consumption of natural gas and the production temperature of the produced asphalt has been developed. As a result of this study, the natural gas consumption per ton depending on the mixing (production) temperature in the batch type asphalt plant can be estimated by using the following equation

$$\text{Natural gas consumption}\left(\frac{\mathrm{m}^3}{\mathrm{ton}}\right) = 0.0935\text{xMixing temperature}(^\circ\mathrm{C}) - 7.6635 \tag{1}$$

3.3. CO2 emissions

One of the major environmental concerns regarding the utilization of high temperatures during the asphaltic material construction is the emission of CO_2. Mallick and Bergendahl (2009) investigated the total CO_2 emission to produce HMA [29]. Their study aimed to develop a model to estimate the CO_2 emission generated by the mixing (production) temperature of bitumen samples. For this purpose, the CO_2 emission of bitumen samples involving WMA additives was laboratory-measured using the Draeger equipment. Data for the CO2 emissions model were assembled at four temperatures (110, 125, 155, and 175 °C) for mixtures prepared using PG 64–28 bitumen with 1.5% Sasobit® content and at three temperatures (125, 155, and 175 °C) for mixtures without Sasobit®. The bitumen content varying from 4% to 7% was considered. In addition, all mixtures were prepared with 1000 g of an aggregate mix containing 60% of stone (coarse aggregate, bulk specific gravity: 2.690 and absorption: 0.5%) and 40% of sand (fine aggregate, bulk specific gravity: 2.600 and absorption: 0.8%). The data of the experimental results were collected at several temperatures over a range of bitumen contents. A linear analysis was conducted using different dependent variables such as mixing temperature, bitumen content, and WMA additives percentage. Among the dependent variables, the mixing temperatures showed a very significant relationship with CO2 emissions. Consequently, the relationship between the mixing temperature and the CO2 emission is predicted as in Eq. (2).

$$Cco2 = 2.175 \quad e^{0.039 \quad T} \tag{2}$$

where C_{CO2} is the CO2 concentration in ppm expected in the 2000 ml flask headspace in equilibrium with 200 g of asphalt mixture and T is the mixing temperature in degree Celsius.

4. Results and discussion

4.1. Mixing (production) temperature results

As depicted in Table 7, the mixing temperatures obtained from the ASTM method are the highest among the proposed methods, for both 50/70 and 160/220 penetration grade bitumen. The mixing temperatures determined by the HSR-O method exhibited very similar results with the ASTM method for both PMB samples. The evolution form (HSR-E) yielded lower mixing temperatures compared to the ASTM method. The implementation of this method is designed based on non-Newtonian behavior, which is clearly detected in PMB samples. However, this method is not suitable for base and WMA samples since they all exhibited Newtonian behavior at elevated temperatures.

For the ZSV method, the results for PMB samples involving Elvaloy have shown a noticeable reduction in mixing temperatures compared to the ASTM method. On the other hand, the application of the ZSV method for the base and WMA bitumen samples is not appropriate due to the Newtonian behavior of such materials.

The estimated temperature results demonstrated a discernible reduction in mixing temperatures compared to the ASTM method for PMB samples when the SSF method is used. However, the obtained mixing temperatures for base bitumen did not show a significant reduction compared to the ASTM method. On the other hand, the SSF method for the WMA samples involving organic additives led to lower mixing temperatures compared to the ASTM method.

4.2. Energy consumption results

Depending on the previous studies, electricity and natural gas consumption were priced for 100 000 tons of annual asphalt in the batch type asphalt plant as a result of the model studies conducted on the modified and unmodified bitumen samples with 50/70 and 160/220 penetration grades. Detailed analyses are given in Tables 8 and 9.

Tables 8 and 9 demonstrate the variation in production temperature for each bituminous sample, with total consumption for 100 000 tons of asphalt. The analysis results demonstrated that the decrease in the mixing temperature resulted in a reduction in asphalt production. This is because the independent variable during the analysis is the mixing temperature.

Table 7
Mixing (production) temperature for 50/70 and 160/220 bitumen grades involving different additive types.

	50/70 Pen. Grade Sample	160/220 Pen. Grade Sample
Base bitumen		
ASTM D 2493	152–158	141–146
HSR-O	NB	NB
HSR-E	NB	NB
ZSV	NB	NB
SSF	152	140
PMB (SBS)		
ASTM D 2493	186–192	174–180
HSR-O	181–187	170–175
HSR-E	170–175	152–158
ZSV	151.5	145.5
SSF	166	148
PMB (Elvaloy)		
ASTM D 2493	165–170	154–158
HSR-O	162–167	152–157
HSR-E	152–155	136–141
ZSV	148.7	140
SSF	157	142
WMA (Organic)		
ASTM D 2493	146–153	135–140
HSR-O	NB	NB
HSR-E	NB	NB
ZSV	NB	NB
SSF	133	124
WMA (Chemical)		
ASTM D 2493	146–151	136–141
HSR-O	NB	NB
HSR-E	NB	NB
ZSV	NB	NB
SSF	136	124

Table 8
Electricity and natural gas consumption per 100 000 tons of annual for 50/70 asphalt manufacturing.

Method	Mixing Temperature (°C)	Natural Gas Consumption (USD)	Electricity Consumption (USD)	Total cost (USD)	Change according to ASTM (%)
	Base bitumen				
ASTM	155	1.53E+05	3.92E+04	1.92E+05	–
	SBS Polymer				
ASTM	189	2.25E+05	7.54E+04	2.99E+05	
HSR-O	184	2.13E+05	6.78E+04	2.82E+05	-6
HSR-E	172.5	1.89E+05	5.46E+04	2.45E+05	-18
ZSV	151.5	1.46E+05	3.47E+04	1.80E+05	-40
SSF	166	1.76E+05	4.90E+04	2.25E+05	-25
	Elvaloy Polymer				
ASTM	167.5	1.79E+05	4.90E+04	2.29E+05	–
HSR-O	164.5	1.73E+05	4.42E+04	2.17E+05	-5
HSR-E	153.5	1.50E+05	3.47E+04	1.84E+05	-19
ZSV	148.7	1.40E+05	3.07E+04	1.70E+05	-25
SSF	157	1.57E+05	3.92E+04	1.96E+05	-14
	Organic WMA Additive				
ASTM	149.5	1.41E+05	3.07E+04	1.72E+05	–
SSF	133	1.07E+05	2.15E+04	1.28E+05	-25
	Chemical WMA Additive				
ASTM	148.5	1.39E+05	3.07E+04	1.70E+05	–
SSF	136	1.13E+05	2.42E+04	1.37E+05	-19

Table 9
Electricity and natural gas consumption per 100 000 tons of annual for 160/220 asphalt manufacturing.

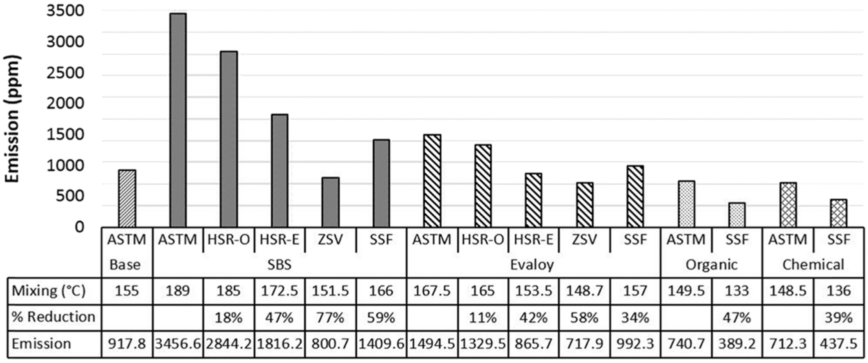
Method	Production Temperature (°C)	Natural Gas Consumption (USD)	Electricity Consumption (USD)	Total cost (USD)	Change according to ASTM (%)
	Base bitumen				
ASTM	143.5	1.29E+05	2.73E+04	1.56E+05	–
	SBS Polymer				
ASTM	180.5	2.06E+05	6.39E+04	2.75E+05	
HSR-O	177	1.99E+05	6.09E+04	2.60E+05	-5
HSR-E	165	1.74E+05	4.42E+04	2.17E+05	-20
ZSV	148.6	1.39E+05	3.07E+04	1.70E+05	-38
SSF	154	1.50E+05	3.47E+04	1.86E+05	-32
	Elvaloy Polymer				
ASTM	161	1.66E+05	4.42E+04	2.10E+05	–
HSR-O	150.5	1.43E+05	3.47E+04	1.79E+05	-15
HSR-E	138	1.17E+05	2.42E+04	1.41E+05	-32
ZSV	125	9.01E+04	1.21E+04	1.02E+05	-51
SSF	142	1.26E+05	2.73E+04	1.53E+05	-27
	Organic WMA Additive				
ASTM	136	1.13E+05	2.42E+04	1.37E+05	–
SSF	120	7.97E+04	1.07E+04	9.05E+04	-34
	Chemical WMA Additive				
ASTM	137.5	1.16E+05	2.42E+04	1.40E+05	–
SSF	129	9.84E+04	1.21E+04	1.11E+05	-21

As seen in Tables 8 and 9, the production temperature plays a significant role in the total cost of the asphalt mixtures., The temperatures obtained by the ZSV method resulted in the lowest energy cost compared to the ASTM method for both 50/70 and 160/220 bitumen involving polymer, while the temperatures determined by HSR-O showed less impact on the total energy cost. For bitumen samples produced with WMA additives, it can be noticed that the temperatures obtained by the SSF method have decreased the estimated energy cost, compared to the ASTM. Also, among the WMA additives, bitumen samples involving the organic type of additive resulted in the lowest estimated energy cost compared to the chemical. This result is attributed to the lowest obtained temperature requirement for the production of the bitumen samples involving chemical WMA additives.

4.3. CO2 emission results

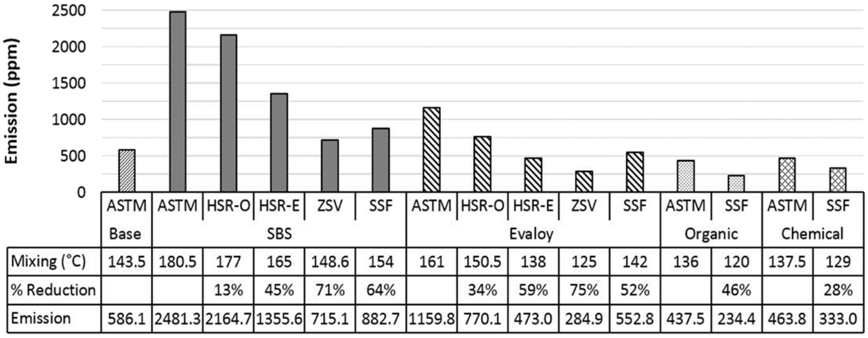
The emission concentration was estimated based on the model suggested by Mallick and Bergendahl (2009). The possible reduction percentages compared to the ASTM method are calculated for both 50/70 and 160/220 penetration grades bitumen involving different additives (Figs. 2 and 3).

As seen in Figs. 2 and 3, the more the decrease in the production temperatures, the more the reduction in carbon emission. The



	Base	SBS					Evaloy					Organic		Chemical	
	ASTM	ASTM	HSR-O	HSR-E	ZSV	SSF	ASTM	HSR-O	HSR-E	ZSV	SSF	ASTM	SSF	ASTM	SSF
Mixing (°C)	155	189	185	172.5	151.5	166	167.5	165	153.5	148.7	157	149.5	133	148.5	136
% Reduction			18%	47%	77%	59%		11%	42%	58%	34%		47%		39%
Emission	917.8	3456.6	2844.2	1816.2	800.7	1409.6	1494.5	1329.5	865.7	717.9	992.3	740.7	389.2	712.3	437.5

Fig. 2. CO2 emission results for 50/70 bitumen samples involving different additive.



	Base	SBS					Evaloy					Organic		Chemical	
	ASTM	ASTM	HSR-O	HSR-E	ZSV	SSF	ASTM	HSR-O	HSR-E	ZSV	SSF	ASTM	SSF	ASTM	SSF
Mixing (°C)	143.5	180.5	177	165	148.6	154	161	150.5	138	125	142	136	120	137.5	129
% Reduction			13%	45%	71%	64%		34%	59%	75%	52%		46%		28%
Emission	586.1	2481.3	2164.7	1355.6	715.1	882.7	1159.8	770.1	473.0	284.9	552.8	437.5	234.4	463.8	333.0

Fig. 3. CO2 emission results for 160/220 bitumen samples involving different additive.

highest carbon emission reductions were observed by the application of the ZSV method for both 50/70 and 160/220 PMB samples because the lowest production temperatures were obtained by the ZSV method. For the samples containing WMA additives, the production temperatures calculated by the SSF method resulted in a substantial reduction in carbon emission compared to the ASTM method. Moreover, similar to the estimation of energy cost, the utilization of organic WMA additive caused the lowest carbon emission since it has the lowest production temperature among all samples.

5. Conclusions

There are some economic and environmental concerns related to the utilization of HMA. In this paper, the influences of the changes in production temperature have been evaluated in terms of the abovementioned concerns. A linear relationship is noticed between the production temperature and energy consumption for the batch type asphalt plant. The warm mix asphalt samples have lower energy consumption compared to the other samples due to the lower mixing temperatures required during the construction. The utilization of the SSF seemed to be preferable since it yielded even lower temperatures than the ASTM method and that significantly reduced the total cost of the required energy for production. For PMB samples, the utilization of the temperatures obtained by ZSV is desirable with regard to the environmental perspectives because it depicted the lowest CO$_2$ emission compared to the ASTM method. The conclusion of this study covers the impact of the mixing temperature as the only independent parameter on the total cost of the asphalt mixture as well as the generated environmental problems. More research should be carried out to include more parameters and different additive types for different asphalt plants.

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.

Acknowledgements

This research was sponsored by the Department of Scientific Research projects, Dokuz Eylul University under the project number 2019. KB.FEN.021 for which the authors are greatly indebted. The authors are also thankful to the Graduate School of Natural and Applied Sciences of Dokuz Eylul University for its support.

References

[1] B. Aktas, S. Aytekin, S. Aslan, Evaluation of typical WMA additives on design parameters of SMA mixtures, Rev. Constr. 18 (3) (2019), 409–17.
[2] A. Almusawi, B. Sengoz, D. Kaya Ozdemir, A. Topal, Predicting mixing and compaction temperatures of polymer modified bitumen, Celal Bayar Üniv. Fen Bilim. Derg. 16 (3) (2020), 263–68.
[3] I. Androjić, Z.D. Alduk, Analysis of energy consumption in the production of hot mix asphalt (batch mix plant), Can. J. Civ. Eng. 43 (2016) 12.
[4] ASTM (American Society for Testing and Materials), Standard practice for viscosity-temperature chart for asphalt binders, 2016.
[5] M. Shishehboran, H. Ziari, A.H. Korayem, M. Hajiloo, Environmental and mechanical impacts of waste incinerated acidic sludge ash as filler in hot mix asphalt, Case Stud. Constr. Mater. 14 (2021), e00504.
[6] Z.A. Jattak, N.A. Hassan, M.K.I.M. Satar, Moisture susceptibility and environmental impact of warm mix asphalt containing bottom ash, Case Stud. Constr. Mater. 15 (2021), e00636.
[7] O.I. Olanrewaju, D.J. Edwards, N. Chileshe, Estimating on-site emissions during ready mixed concrete (RMC) delivery: a methodology, Case Stud. Constr. Mater. 13 (2020), e00439.
[8] P. Georgiou, A. Loizos, Environmental assessment of warm mix asphalt incorporating steel slag and high reclaimed asphalt for wearing courses: a case study, Road Mater. Pavement Des. 22 (sup1) (2021) S662–S671.
[9] C. Oreto, R. Veropalumbo, N. Viscione, S.A. Biancardo, F. Russo, Investigating the environmental impacts and engineering performance of road asphalt pavement mixtures made up of jet grouting waste and reclaimed asphalt pavement, Environ. Res. 198 (2021), 111277.
[10] M. Wang, C. Wang, S. Huang, H. Yuan, Study on asphalt volatile organic compounds emission reduction: a state-of-the-art review, J. Clean. Prod. 318 (2021), 128596.
[11] X. Yang, Z. You, D. Perram, D. Hand, Z. Ahmed, W. Wei, S. Luo, Emission analysis of recycled tire rubber modified asphalt in hot and warm mix conditions, J. Hazard. Mater. 365 (2019) 942–951.
[12] B.W. Ang, T.F. Fwa, T.T. Ng, Analysis of process energy use of asphalt-mixing plants, Energy 18 (7) (1993) 769–777.
[13] T.J. Young, Energy Analysis for Hot Mix Plants. Rev 020309/Permission of Use Required. Technical Training and Advisory Services Company, 2008. Http:// Www. Hotmixproduction. Com. (Accessed 12.04. 2020).
[14] R. Jenny, CO2 reduction on asphalt mixing plants potential and practical solutions, 2009. Accessed 10 May 2020. http://railknowledgebank.com.
[15] K. Cervarich, Cooled and ready to serve? Industry explores new warm-mix technologies developed in Europe, Roads Bridges 41 (2003) 9.
[16] J.K. Davidson, Warm asphalt mix technology: an overview of the process in Canada, in: Annual Conference of the Transportation Association of Canada Transportation Association of Canada (TAC), 2008.
[17] W. Grabowski, L. Janowski, Issues of energy consumption during hot mix asphalt (HMA) production. In Modern Building Materials, Structures and Techniques. Proceedings of the International Conference 10, 2010, 89.
[18] 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.
[19] H. Sivilevicius, Application of expert evaluation method to determine the importance of operating asphalt mixing plant quality criteria and rank correlation, Balt. J. Road Bridge Eng. 6 (1) (2011) 48–58.
[20] A. Almusawi, B. Sengoz, A. Topal, Evaluation of mechanical properties of different asphalt concrete types in relation with mixing and compaction temperatures, Constr. Build. Mater. 268 (2021), 121140.
[21] A. Almusawi, B. Sengoz, A. Topal, Investigation of mixing and compaction temperatures of modified hot asphalt and warm mix asphalt, Period. Polytech. Civ. Eng. 65 (1) (2021) 72–83.
[22] M. Solaimanian, W. Kennedy, Mixing and compaction temperatures for hot mix asphalt concrete. Center for Transportation Research, Report No. 1250-5, 2000.
[23] J. Ideker, D. Hazlett, Evaluation of viscosity values for mixing and compaction temperatures, J. Mater. Civ. Eng. 18 (4) (2006), 545–53.
[24] M.A. Khatri, Selection of mixing and compaction temperatures for hot mix asphalt mixtures produced with modified binders (Ph.D. diss.), The University of Wisconsin-Madison, 2005.
[25] R.C. West, D.E. Watson, P.A. Turner, J.R. Casola, Mixing and compaction temperatures of asphalt binders in hot-mix asphalt. National Cooperative Highway Research Program, Report No 9-39, 2010.
[26] Z. Temren, İ. Sönmez, Asfalt ve Beton Karışımların İmalatında Enerji Tüketimi ve Karbon Ayak İzi İle İlgili Bir Çalışma [A Study on Energy Consumption and Carbon Footprint in the Production of Asphalt and Concrete Mixtures]. 6. Ulusal Asfalt Sempozyum ve Sergisi, Ankara, 2013, pp. 137–149.
[27] J. Bražiūnas, H. Sivilevičius, Heat transfer and energy loss in bitumen batching system of asphalt mixing plant, in: 9th International Conference on Environmental Engineering. Vilnius, Lithuania 20406080, 2014, pp. 100–120.
[28] I. Androjić, Z.D. Alduk, Analysis of energy consumption in the production of hot mix asphalt (batch mix plant), Can. J. Civ. Eng. 43 (2016) 12.
[29] R.B. Mallick, J. Bergendahl, A laboratory study on CO_2 emission from asphalt binder and its reduction with the use of warm mix asphalt, Int. J. Sustain. Eng. 2 (4) (2009) 275–283.