CHAPTER 7

ECONOMIC AND ENVIRONMENTAL IMPACT OF WMA TECHNOLOGIES

7.1 Preface

In India, the majority of National and State highways are constructed with hot mix asphalt (HMA) as a surface layer. Producing HMA, a mixture of graded mineral aggregates, asphalt binder, and air voids, requires energy in the form of heat (at temperatures > 150°C) [3,4]. With infrastructure growing at an exponential rate, this energy requirement has enormous implications for the social and economic development of the country [623]. It has been reported that the production of asphalt mixtures reached 1.5 billion tons in 2007 and has been increasing gradually [624]. This enormous production consumes approximately 136×10^6 MWh energy per year [625]. Predominantly the energy required for the asphalt mixture production is consumed during heating the asphalt binder, drying the mineral aggregates, and mixing the mineral aggregates with the asphalt binder [626,627]. Notably, 70-100 kWh per ton of energy is required for the drying and heating process, whereas only 5-8 kWh is needed for the transportation and storage of asphalt mixtures [625,628]. In the same context, [629] observed that almost 70-80% of energy consumption and emissions exhibit during the production of asphalt mixtures, while the amount is less than 20% for the transportation stage. Such high energy consumption during production markedly increases the cost of construction and leads to the emission of greenhouse gases (GHG).

In terms of GHG emissions, the production of HMA emits a large amount of CO_2 (Carbon dioxide), CH_4 (Methane), and N_2O (Nitrous oxide) gases, which negatively affects the health of the workers and the environment [630,631]. Among these gases, CO_2 is considered to have a higher impact on the environmental footprint [632,633]. This is one of the reasons for quantifying the global warming potential (GWP) of the GHG in terms of equivalent CO_2. A review of roadway lifecycle assessment indicated that the total amount of CO_2 emissions released during the production of asphalt mixtures amounted to 200-600 tonnes per mile of road in the year 2010 [634].

The total amount of GHG emitted during asphalt mixture production is related to the quantity and the type of fuel used [635]. In India, diesel, natural gas, heavy oil, coal, low sulphur heavy stock (LSHS), furnace oil, and light diesel oil (LDO) are commonly used for generating heat in the mixing plant. Eventually, GHG emissions can be minimized by adopting a cleaner energy source. Though natural gas is a cleaner energy source compared to other fuel types, the choice of using a fuel for any project depends on various other factors such as its availability and cost [636]. To reduce the environmental concerns imposed through asphalt pavement construction, several studies have investigated the potential of alternative construction approaches to reduce the asphalt mixture's production temperatures, thereby reducing the energy required and GHG emissions. For instance, [366] reported that lessening the production temperature by 10°C minimizes the heavy oil consumption by 11.8 kWh (1 liter) and CO_2 emissions by 1 kg/ton.

Since WMA reduce the production temperature, it is desirable to study the impact of WMA additives on the economic and environmental burdens. A comparative study between WMA and HMA showed that the addition of WMA additives lowers the energy consumption by about 5-13%, depending upon the range of temperature reduction [443]. Several recent studies also demonstrate the benefits of WMA application to reduce GHG emissions. [425] found that the application of WMA technology lowers GHG emissions by 20-35% compared to the conventional HMA. It was also found that per ton of WMA mixture production lowers GHG emissions by 4.1 to 5.5 kg (in terms of equivalent CO_2). Many studies have been done on the use of WMA technology for the production of asphalt mixtures [140,160,174,290,313]. Most of the researches (done in laboratory and in field) has evaluated the performance of WMA modified binders and/or mixtures, and compared the results with HMA [37,43,90,171,373,637]. However, quantitative studies on economic and environmental benefits gained by using various WMA technologies (organic, chemical and foaming based), considering the use of a variety of fuel types in the mixing plant, are scanty.

This chapter details the energy-related cost and amount of GHG emissions imparted by producing WMA mixtures based on a theoretical approach. Four different aggregate and asphalt binder combinations were theoretically examined based on different available equations and test parameters. These WMA combinations differed based on aggregate source and type of base asphalt binder. The combinations are (1) granite aggregate in VG30 mixtures (GVG), (2) dolomite aggregate in VG30 mixtures (DVG), (3) granite aggregate in PMB40 mixtures (GP), and (4) dolomite aggregate in PMB40 mixtures (DP). A representative sample of 1000 kg asphalt mixture was hypothesized throughout the analysis to benchmark the energy consumption and GHG emissions in a comparative framework. Indian pricing system has been used for performing the cost analysis. Different factors such as fuel type and type of WMA additive were varied during the analysis. It is envisaged that the data presented and the research carried out in this study will be helpful for asphalt industries, policymakers, and environmental authorities or decision-makers for the implementation of WMA in pavement construction.

7.2 Experimental Approach

7.2.1 Environmental Life Cycle Assessment (ELCA)

ELCA facilitates the estimation of energy-related costs and the total environmental burden (in terms of GHG emissions) of any material during its entire lifespan [411,638,639]. To compare HMA and WMA mixtures, the overall ELCA should consider the environmental impacts from all possible sources, such as extraction, production, transportation, construction, utilization, maintenance, milling, and final disposal at the end of service life. However, while comparing HMA and WMA mixtures at equal boundary variables (based on the types of aggregate and asphalt binder, aggregate moisture content, type of asphalt plant, distance between construction site and asphalt plant, and climatic condition), the difference in production temperatures between these two technologies is the only variable that needs to be considered. In this study, some of the WMA additives were stirred with the asphalt binder before preparing asphalt mixtures. The amount of energy consumed and emissions released during this process are not considered as the base asphalt binder was also stirred at similar test conditions to maintain consistency. It should also be noted that the manufacturing and transportation of WMA additives may further release emissions and will require additional energy. As per previous literature [141,366,422,423,626,629,640], the contribution from manufacturing and transportation of additives is negligible compared to the variation caused by the change in production temperatures and hence is neglected in this study. As different fuel types can be used in the mixing plant, their effect has been considered for performing the ELCA.

7.2.2 Calculation of Energy Consumption and GHG Emissions

Generally, energy consumed during the production of asphalt mixtures can be divided into three categories: (1) energy required in the rotary dryer [641], (2) energy needed for heating asphalt binder [642], and (3) energy required for the operation of asphalt plant [643]. Additionally, a part of the energy is required for operating hot storage bins, pugmills, and transportation of asphalt mixtures [636,644]. As almost 80-90% of the total energy is consumed for heating and mixing the mineral aggregates and the asphalt binder, the effect of other variables was not considered in the analysis.

The heat energy required (H) for drying the aggregates, heating the asphalt binder, and water evaporation (during the drying process) can be determined using Equations 7.1-7.6, as shown in Table 7.1. These equations provide a theoretical estimation of the energy consumption required to produce asphalt mixtures with 100% efficiency [645]. The values of various parameters involved in Equations (7.1-7.5) are given in Table 7.2. Seven different fuels were considered to assess the effect of fuel type: viz, diesel, heavy oil, natural gas, coal, LSHS, furnace oil, and LDO. The amount of fuel consumption (F) was determined using the energy consumption, calorific value (or the heating power of the fuel) (Φ), and density of the fuel (ρ) as indicated in Equation 7.7. The values of the parameters used for calculating F are provided in Table 7.3. After assessing the value of F, the total cost for each fuel type was determined by multiplying the unit price of fuel with the value of F.

Table 7.1. Equations used for the evaluation of heat energy and fuel consumption

Heat Energy Consumption	**Equation**	**Equation Number**
Heating aggregates	$H_a = S_a \times M_a \times (T_a - t_a)$	(7.1)
Heating water	$H_w = S_w \times \frac{m}{100} \times M_a \times (t_b - t_a)$	(7.2)
Water vaporisation	$H_v = L_v \times \frac{m}{100} \times M_a$	(7.3)
Heating steam	$H_s = S_s \times \frac{m}{100} \times M_a \times (T_a - t_b)$	(7.4)
Heating asphalt binder	$H_b = S_b \times M_b \times (T_b - t_a)$	(7.5)
Total	$H = H_a + H_w + H_v + H_s + H_b$	(7.6)
Fuel Consumption	$F = \frac{H}{\Phi \times \rho}$	(7.7)

Note: T_a and T_b indicate heating/mixing temperatures for aggregates and asphalt binder, respectively. In the present study, T_a and T_b have same meaning, however, it may change depending on the selection of heating/mixing temperatures of aggregate and asphalt binder. Different indications of T_a and T_b are shown so that the equation can be used universally. The unit of heat energy consumption is Joule (J).

Table 7.2. Values of variables used for the evaluation of heat energy [10,443]

Variables	**Notations**	**Unit**	**Value**	
Ambient Temperature	t_a	°C	25	
Boiling point of water	t_b	°C	100	
Specific heat of aggregates	S_a	J/kg.°C	G	D
			850	900
Specific heat of water	S_w	J/kg.°C	4200	
Specific heat of steam	S_s	J/kg.°C	1850	

Specific heat of asphalt binder	S_b	J/kg.°C	2093.4			
Moisture content in aggregates	m	%	2			
Latent heat of vaporization	L_v	J/kg	2250000			
Mass of asphalt mixture	M_T	Kg	1000			
Optimum binder content	OBC	%	GVG	DVG	GP	DP
			5.8	5.6	6	5.9
Mass of aggregates	M_a	Kg	GVG	DVG	GP	DP
			942	944	940	941
Mass of asphalt binder	M_b	Kg	GVG	DVG	GP	DP
			58	56	60	59

Note: G and D indicate granite and dolomite aggregates, respectively.

Table 7.3. Value of constant parameters for the evaluation of fuel consumption [646,647]

Fuel Type	**Φ (MJ/kg)**	**ρ (g/cm^3)**	**Oxidation/Combustion rate**
Diesel	45.6	0.835	0.98
Heavy Oil	39.0	0.905	0.98
Natural Gas	52.2	0.800	-
Coal	30.2	-	0.9
Low Sulphur Heavy Stock	44.0	0.880	-
Furnace Oil	43.0	0.900	-

Light Diesel Oil	43.0	0.855	-

The production of asphalt mixtures consumes energy in from fuel and electricity. In India, the majority of the asphalt plants utilize fuel for drying mineral aggregates, heating asphalt binders, and preparing final asphalt mixtures. At the same time, electric energy is required to operate types of machinery. The burning of these fuels leads to GHG emissions, including CO_2, CH_4, and N_2O.

There are four different emission estimation tools: (1) sampling or direct measurement [443,648], (2) mass balance principle [641,649], (3) analysis of fuel consumption [419,650], and (4) energy emission factors (EEF) based approach [651,652]. The selection of a tool depends on the availability of relevant data to estimate GHG emissions. The present study used EEF technique as these factors are easily accessible from the reports provided by Intergovernmental Panel on Climatic Change (IPCC) and various previous studies [10,647,651,653]. Table 7.4 presents the values of EEF specified by IPCC [651] to measure the GHG emissions released from different fuel types. Using the available data, Equation 7.8 was used to estimate the GHG emissions (individually for CO_2, CH_4, and N_2O) in kilogram per tonne (kg/t) of asphalt mixture production. This estimation approach is in line with the past studies [636,647], which have used similar equations for calculating the GHG emissions from energy consumption.

$$E = Q \times \Phi \times \rho \times \alpha \times EEF \qquad (7.8)$$

Where, E is the emissions from energy consumption (kg/t), Q is the quantity of fuel (kg), Φ is the calorific value of the fuel (MJ/kg), ρ is the density of fuel (g/cm^3, if required for unit conversion), α is the oxidation/combustion rate of fuel, and EEF represents energy emission factor (mg/MJ).

To evaluate total GHG emissions ($\sum E$) in terms of equivalent $kgCO_2$ (Equation 7.9), Global Warming Potentials (GWP) were incorporated in Equation 7.8. IPCC [651] recommend using GWP to compare different GHG's at the same scale. It is an extent of how much energy the emission of 1 tonne of a gas will absorb over a time span (generally 100 years), compared to the emission of 1 tonne of CO_2 [633]. CO_2 was taken as a reference as it remains in the climate for a very long time period (~1000 years) [653]. A higher value of GWP for any gas, relative to CO_2, indicates that the particular gas warms the earth more drastically. As per the values proposed by IPCC [651], GWP for CO_2, CH_4, and N_2O are taken as 1, 25, and 298, respectively. The other parametric values used in Equation 7.9 are presented in Table 7.3. The value of 'i' in equation 7.9 represents the type of GHG, where i =1, 2, and 3 refers to CO_2, CH_4, and N_2O, respectively.

$$\sum E = Q \times \Phi \times \rho \times \alpha \times \sum_{i=1}^{3} EEF_i \times GWP_i \qquad (7.9)$$

Table 7.4. Energy emission factors for different fuels [651,654]

EEF (mg/MJ)	**Diesel**	**Heavy Oil**	**Natural Gas**	**Coal**	**LSHS**	**Furnace Oil**	**LDO**
CO_2	74100	77400	56100	94600	72930	72930	74100
CH_4	3	3	1	1	3	3	3
N_2O	0.6	0.6	0.1	1.5	0.6	0.6	0.6

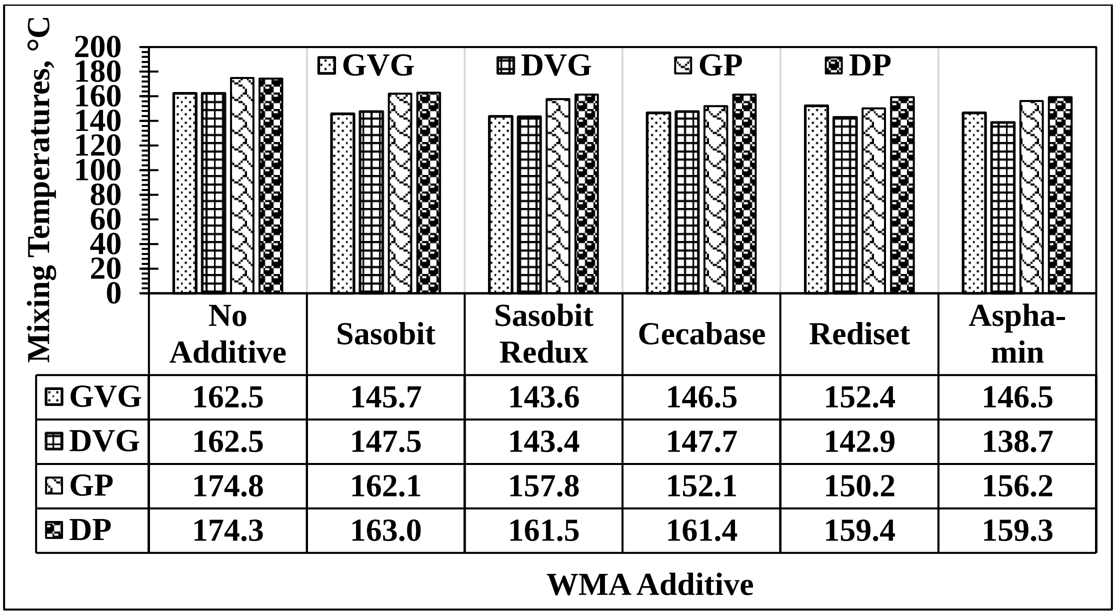
7.3 Results and Discussion

7.3.1 Energy Consumption and Cost Savings

Based on the production temperature requirement of HMA and WMA used in this study (as shown in the Figure 7.1), heat energy was calculated using the equations given in

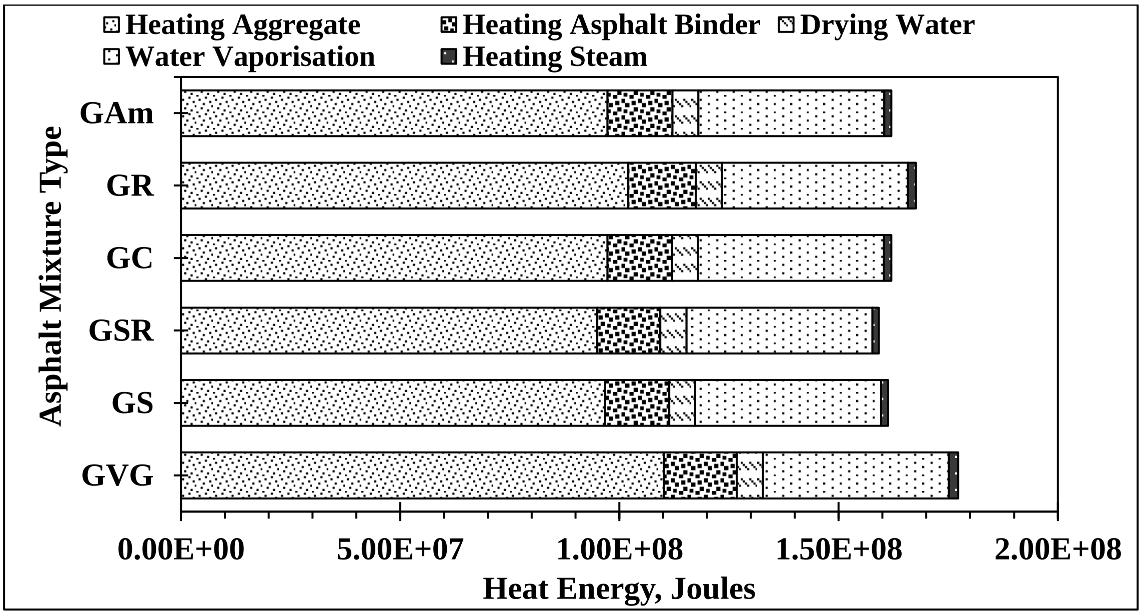
Table 7.1. Figure 7.2 (a-d) shows the variation in the amount of heat energy required for different processes. As it can be seen, the average maximum amount of heat energy is needed for heating the aggregates (60%), followed by water vaporization (25%), heating of asphalt binder (10%), heating water (4%), and removal of steam (1%). These quantifications are independent of any variables, including the type of base asphalt binder, aggregate source, and WMA technology. It should be noted the energy required for heating water and its vaporization was found to be the same for each combination of aggregate and asphalt binder, irrespective of WMA additive, (for example: one such combination is granite aggregate with PMB40 or dolomite aggregate with VG30, as discussed in the preceding section). This may be due to the consideration of the same aggregate source, quantity of aggregates, and moisture content in the aggregates for each WMA and HMA mixtures in a particular combination. Additionally, the determination of heat energy for these stages is based on the boiling point of water and latent heat of vaporization, rather than the production temperature of asphalt mixtures, which is variable in all the combinations. Therefore, the change in heat energy consumption with the addition of WMA additives is predominantly due to the heating of mineral aggregates, asphalt binder, and steam removal. Since the production of conventional HMA requires high heating temperatures, the amount of energy consumption is relatively high. On the other hand, the application of WMA technologies lowers the production temperatures and thereby reduces the overall energy consumption. However, the extent of reduction is a function of base asphalt binder, aggregate source, and WMA additive. As expected, use of PMB40 as a base asphalt binder requires high heat energy as compared to VG30 mixtures. This trend was consistent for all the HMA and WMA mixtures considered in this study. Interestingly, the heat energy required for heating water and its vaporization were relatively lower in

PMB40 mixtures. This is because polymer-modified mixtures exhibit higher optimum binder content (OBC), which increases the amount of asphalt binder, and thereby reduces the quantity of mineral aggregates from the total representative mix of 1000 kg. This attribution is independent of aggregate source and WMA additives.

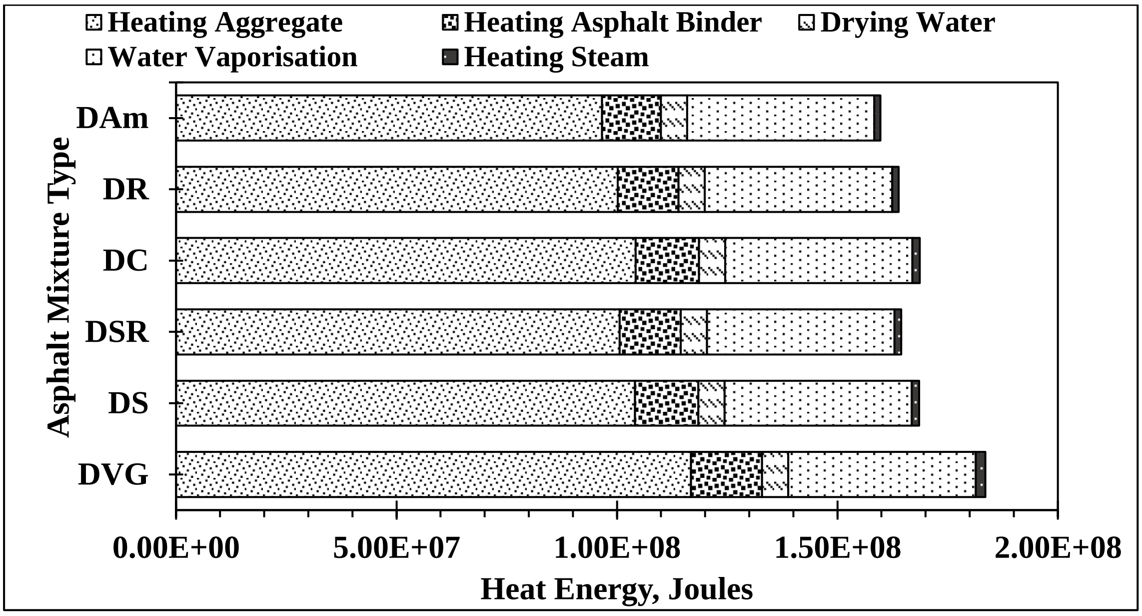


	No Additive	Sasobit	Sasobit Redux	Cecabase	Rediset	Aspha-min
GVG	162.5	145.7	143.6	146.5	152.4	146.5
DVG	162.5	147.5	143.4	147.7	142.9	138.7
GP	174.8	162.1	157.8	152.1	150.2	156.2
DP	174.3	163.0	161.5	161.4	159.4	159.3

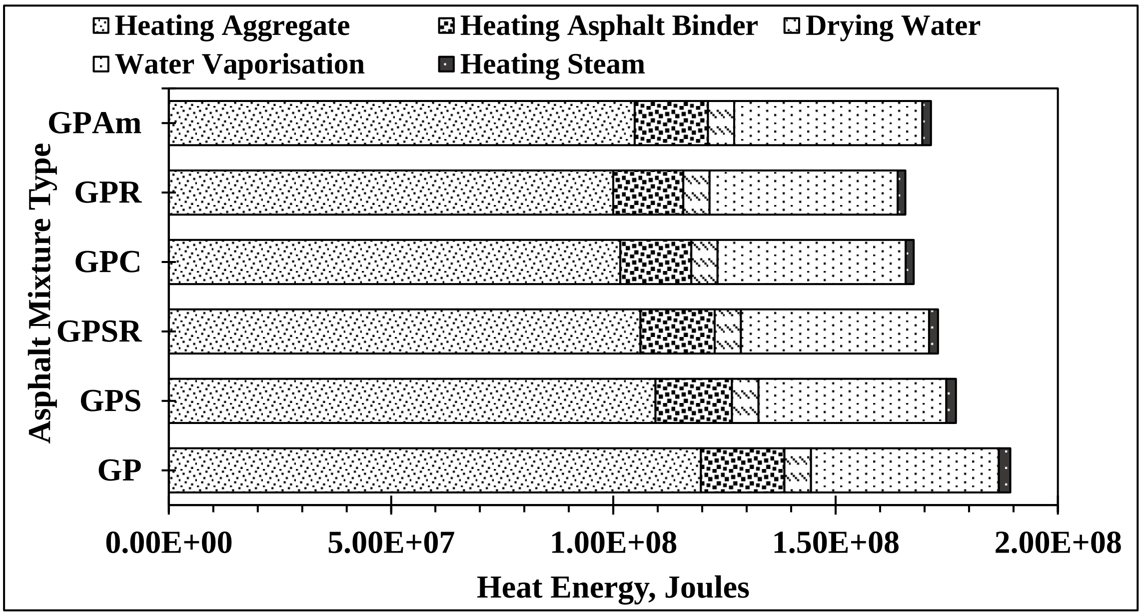
Figure 7.1. Mixing temperatures of different WMA combinations at their optimum dosage



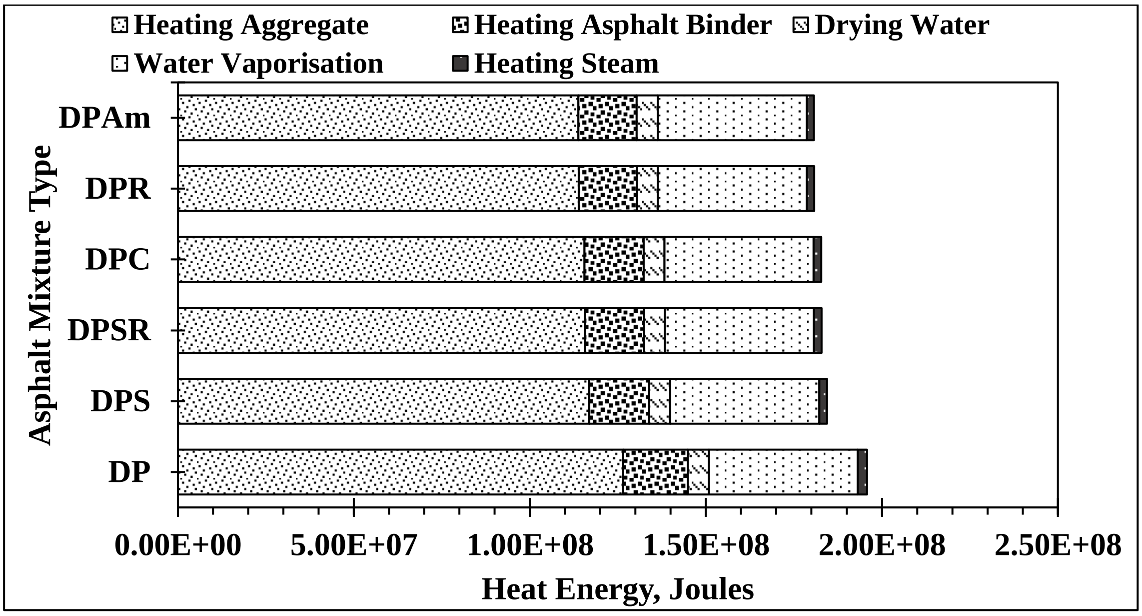
(a)


Heating Aggregate
Heating Asphalt Binder
Drying Water
Water Vaporisation
Heating Steam
Asphalt Mixture Type
DAm
DR
DC
DSR
DS
DVG
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
Heat Energy, Joules

(b)


Heating Aggregate
Heating Asphalt Binder
Drying Water
Water Vaporisation
Heating Steam
Asphalt Mixture Type
GPAm
GPR
GPC
GPSR
GPS
GP
0.00E+00
5.00E+07
1.00E+08
1.50E+08
2.00E+08
Heat Energy, Joules

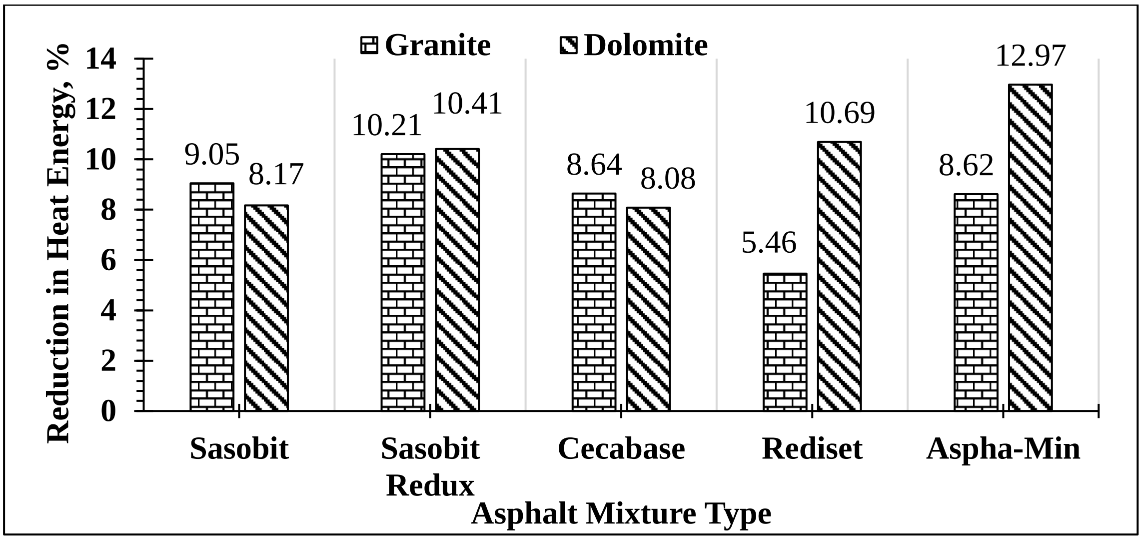
(c)



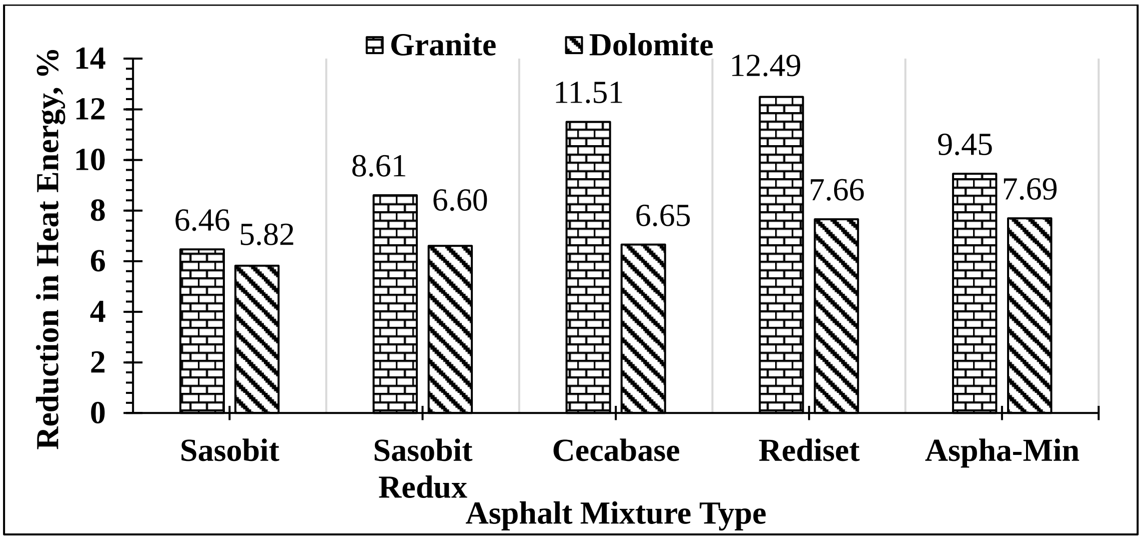
(d)

Figure 7.2. Heat energy consumption for HMA and WMA mixtures with different combinations of aggregate and asphalt binder (a) Granite and VG30, (b) Dolomite and VG30, (c) Granite and PMB40, and (d) Dolomite and PMB40

Figure 7.3a and Figure 7.3b show the percent reduction in heat energy consumption for VG30 and PMB40 asphalt mixtures, respectively. As demonstrated in the figures, the addition of WMA additives in VG30 or PMB40 reduced the heat energy by 5%-13% relative to HMA, irrespective of the aggregate source. In particular, the WMA mixtures prepared with VG30 and granite aggregates indicated a reduction of around 5%-10%, whereas the same mixture with dolomite aggregates reduced the heat energy by 8%-13%, in comparison to HMA. Similarly, in the case of PMB40, the adoption of WMA technologies with granite and dolomite aggregates resulted in 6%-8% and 6%-13% lower energy requirements, respectively. Irrespective of aggregate and base asphalt binder, reduction in energy consumption for organic-based additives ranged from 6%-10%, whereas it varied from 5%-13% and 7%-13% for chemical and foaming-based technologies, respectively. The variation in the range of reduction in heat energy is primarily dependent of several factors, including aggregate source, type of base asphalt binder, and their combination with different WMA additives. In other words, it is a function of mixing temperatures required for the production of asphalt mixtures. Overall, the use of Aspha-Min indicated the highest reduction in heat energy requirement, followed by Rediset, Sasobit Redux, Cecabase, and Sasobit, regardless of any aggregate source and base asphalt binder.



(a)



(b)

Figure 7.3. Reduction in heat energy for WMA mixtures (a) VG30 base asphalt binder and (b) PMB40 base asphalt binder

As mentioned previously, seven different fuel types were examined in the present study, i.e., diesel, heavy oil, natural gas, coal, furnace oil, LSHS, and LDO. The fuel consumption for the production of 1000 kg asphalt mixtures was determined using Equation 7.7 and is shown in Table 7.5 – Table 7.8. As can be seen, the amount of heat energy required for the production of asphalt mixtures is highest for coal-based asphalt plants, whereas it is least when natural gas is the energy source. The ratio of the amount of coal required to generate a fixed quantity of heat energy relative to other fuel types was found to be 1.73, 1.28, 1.26, 1.25, and 1.21 for natural gas, furnace oil and LSHS, diesel, heavy oil, and LDO, respectively. These values are calculated by assuming 100% heat transfer efficiency. The actual economic benefits and cost-saving potential depend on the unit price of the fuel. The unit price of each fuel was obtained from various suppliers, and the average price was used for analysing the fuel consumption as listed in Table 7.9. Although the amount of coal required to produce asphalt mixtures is highest in comparison to other fuel types, the overall cost for producing asphalt mixtures using coal is considerably low. This is attributed to the lower unit cost of coal relative to other fuels. Figure 7.4 (a-d) shows that the addition of WMA additives results in potential cost-saving relative to conventional HMA. Maximum cost savings range from Rs. 25 to 62 for diesel-based asphalt plants, followed by LSHS (Rs. 14 to 35), furnace oil (Rs. 14 to 34), LDO (Rs. 14 to 34), heavy oil (Rs. 13 to 31), natural gas (Rs. 8 to 19), and coal (Rs. 5 to 12). These savings are dependent on the type of aggregate source, base asphalt binder, and WMA additives. In case of granite aggregates (irrespective of fuel type), the addition of Sasobit Redux and Rediset in VG30 and PMB40, respectively, (i.e., GSR, and GPR), indicated maximum cost savings. Similarly, for dolomite aggregates, the use of Aspha-Min with VG30 and PMB40 (i.e., DAm and DPAm), were found to yield more saving in comparison to other WMA additives. For VG30 as the base binder, the addition of Rediset and Cecabase with granite and dolomite aggregates, respectively, indicated the lowest reduction, whereas in PMB40, the incorporation of Sasobit showed the lowest cost savings. These observations and interpretations are irrespective of fuel type.

Table 7.5. Amount and price of fuel to produce 1000 kg HMA and WMA mixtures with granite and VG30

Fuel Type	**Asphalt Mixture**	**GVG**	**GS**	**GSR**	**GC**	**GR**	**GAm**
Diesel	**Q (Litre)**	4.66	4.24	4.18	4.25	4.40	4.26
	P (Rupees)	460.98	419.27	413.93	421.16	435.80	421.26
Heavy Oil	**Q (Litre)**	4.69	4.26	4.21	4.28	4.43	4.28
	P (Rupees)	234.34	213.14	210.42	214.09	221.54	214.15
Natural Gas	**Q (kg)**	3.40	3.09	3.05	3.10	3.21	3.10
	P (Rupees)	142.65	129.74	128.09	130.33	134.86	130.36
Coal	**Q (kg)**	5.87	5.34	5.27	5.36	5.55	5.36
	P (Rupees)	88.06	80.09	79.07	80.45	83.25	80.47
Furnace Oil	**Q (Litre)**	4.58	4.17	4.11	4.19	4.33	4.19
	P (Rupees)	256.55	233.34	230.37	234.39	242.54	234.45
LSHS	**Q (Litre)**	4.58	4.16	4.11	4.18	4.33	4.18
	P (Rupees)	261.00	237.38	234.36	238.45	246.74	238.51
LDO	**Q (Litre)**	4.82	4.39	4.33	4.41	4.56	4.41
	P (Rupees)	255.59	232.46	229.50	233.51	241.63	233.57

Table 7.6. Amount and price of fuel to produce 1000 kg HMA and WMA mixtures with dolomite and VG30

Fuel Type	Asphalt Mixture	DVG	DS	DSR	DC	DR	DAm
Diesel	**Q (Litre)**	4.82	4.43	4.32	4.43	4.31	4.20
	P (Rupees)	477.24	438.23	427.58	438.66	426.21	415.35
Heavy Oil	**Q (Litre)**	4.85	4.46	4.35	4.46	4.33	4.22
	P (Rupees)	242.60	222.78	217.36	222.99	216.66	211.14
Natural Gas	**Q (kg)**	3.52	3.23	3.15	3.23	3.14	3.06
	P (Rupees)	147.68	135.61	132.32	135.75	131.89	128.53
Coal	**Q (kg)**	6.08	5.58	5.45	5.59	5.43	5.29
	P (Rupees)	91.17	83.72	81.68	83.80	81.42	79.34
Furnace Oil	**Q (Litre)**	4.74	4.36	4.25	4.36	4.24	4.13
	P (Rupees)	265.60	243.89	237.96	244.13	237.20	231.16
LSHS	**Q (Litre)**	4.74	4.35	4.25	4.36	4.23	4.13
	P (Rupees)	270.20	248.12	242.09	248.36	241.31	235.16
LDO	**Q (Litre)**	4.99	4.58	4.47	4.59	4.46	4.35
	P (Rupees)	264.60	242.98	237.07	243.21	236.31	230.29

Table 7.7. Amount and price of fuel to produce 1000 kg HMA and WMA mixtures with granite and PMB40

Fuel Type	Asphalt Mixture	GP	GPS	GPSR	GPC	GPR	GPAm
Diesel	**Q (Litre)**	4.97	4.65	4.54	4.40	4.35	4.50
	P (Rupees)	492.29	460.47	449.92	435.65	430.82	445.75

Heavy Oil	**Q (Litre)**	5.01	4.68	4.57	4.43	4.38	4.53
	P (Rupees)	250.26	234.08	228.71	221.46	219.00	226.60
Natural Gas	**Q (kg)**	3.63	3.39	3.31	3.21	3.17	3.28
	P (Rupees)	152.34	142.49	139.23	134.81	133.32	137.94
Coal	**Q (kg)**	6.27	5.86	5.73	5.55	5.49	5.68
	P (Rupees)	94.04	87.96	85.95	83.22	82.30	85.15
Furnace Oil	**Q (Litre)**	4.89	4.58	4.47	4.33	4.28	4.43
	P (Rupees)	273.98	256.27	250.40	242.45	239.76	248.08
LSHS	**Q (Litre)**	4.89	4.57	4.47	4.33	4.28	4.43
	P (Rupees)	278.73	260.71	254.74	246.66	243.92	252.38
LDO	**Q (Litre)**	5.15	4.82	4.71	4.56	4.51	4.66
	P (Rupees)	272.95	255.30	249.45	241.54	238.86	247.14

Table 7.8. Amount and price of fuel to produce 1000 kg HMA and WMA mixtures with dolomite and PMB40

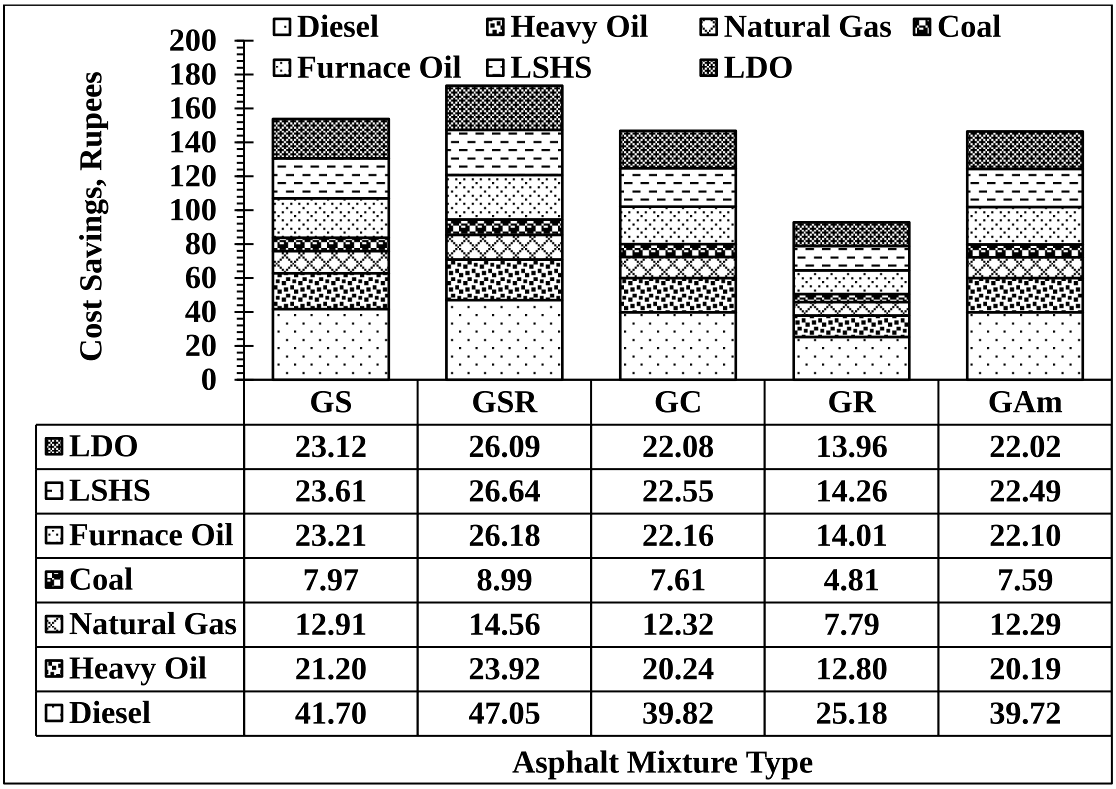
Fuel Type	**Asphalt Mixture**	**DP**	**DPS**	**DPSR**	**DPC**	**DPR**	**DPAm**
Diesel	**Q (Litre)**	5.14	4.84	4.80	4.80	4.75	4.75
	P (Rupees)	509.00	479.39	475.42	475.16	470.01	469.84
Heavy Oil	**Q (Litre)**	5.18	4.87	4.83	4.83	4.78	4.78
	P (Rupees)	258.75	243.70	241.68	241.55	238.93	238.84
Natural Gas	**Q (kg)**	3.75	3.53	3.50	3.50	3.46	3.46
	P (Rupees)	157.51	148.35	147.12	147.04	145.45	145.39
Coal	**Q (kg)**	6.48	6.11	6.05	6.05	5.99	5.98
	P (Rupees)	97.23	91.58	90.82	90.77	89.79	89.75

Furnace Oil	**Q (Litre)**	5.06	4.76	4.72	4.72	4.67	4.67
	P (Rupees)	283.28	266.80	264.59	264.44	261.58	261.49
LSHS	**Q (Litre)**	5.06	4.76	4.72	4.72	4.67	4.67
	P (Rupees)	288.19	271.42	269.17	269.03	266.11	266.02
LDO	**Q (Litre)**	5.32	5.02	4.97	4.97	4.92	4.92
	P (Rupees)	282.21	265.80	263.59	263.45	260.60	260.50

Note: Q and P in Table 7.5 – Table 7.8 indicate quantity and price of the fuel, respectively.

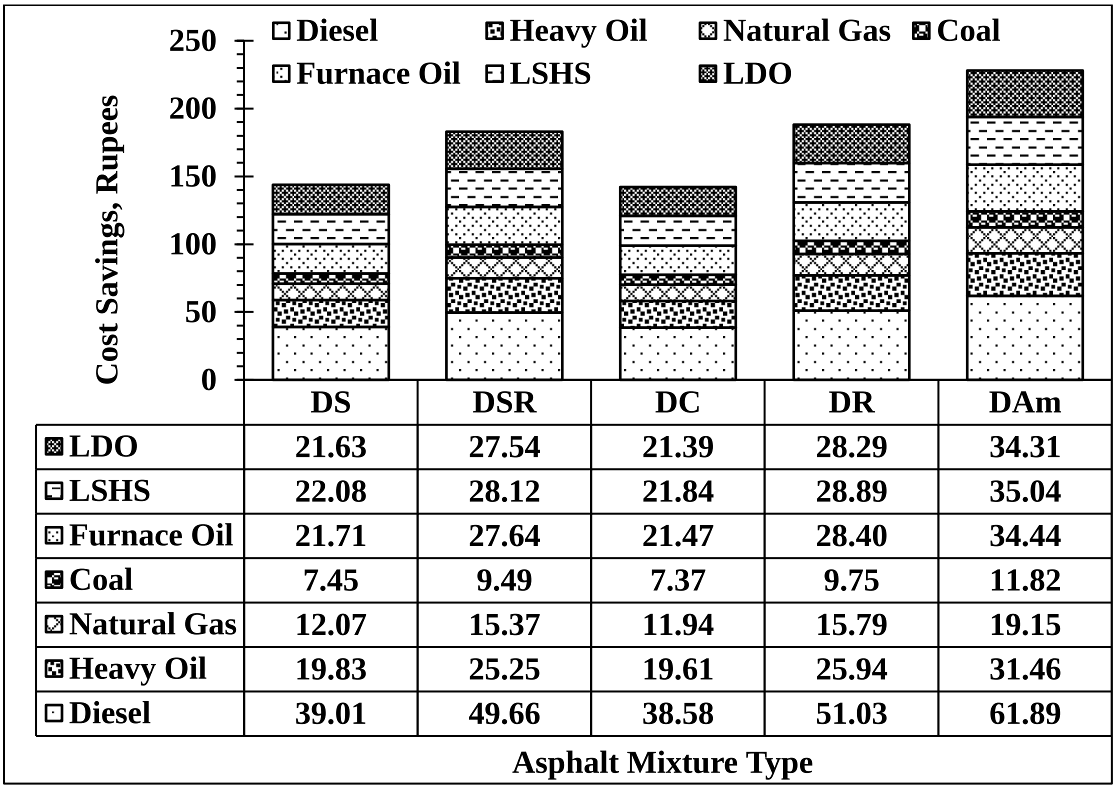
Table 7.9. Unit price of different fuels

Fuel	**Unit**	**Price**
Diesel	per litre	99
Heavy Oil	per litre	50
Natural Gas	per kg	42
Coal	per kg	15
Furnace Oil	per litre	56
LSHS	per litre	57
LDO	per litre	53



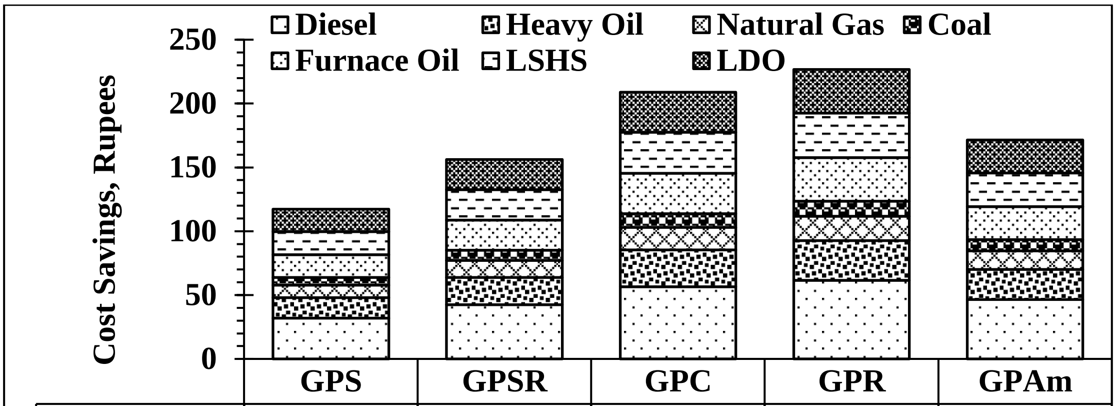
	GS	GSR	GC	GR	GAm
▨ LDO	23.12	26.09	22.08	13.96	22.02
▨ LSHS	23.61	26.64	22.55	14.26	22.49
▨ Furnace Oil	23.21	26.18	22.16	14.01	22.10
▨ Coal	7.97	8.99	7.61	4.81	7.59
▨ Natural Gas	12.91	14.56	12.32	7.79	12.29
▨ Heavy Oil	21.20	23.92	20.24	12.80	20.19
▨ Diesel	41.70	47.05	39.82	25.18	39.72

(a)



	DS	DSR	DC	DR	DAm
▨ LDO	21.63	27.54	21.39	28.29	34.31
▨ LSHS	22.08	28.12	21.84	28.89	35.04
▨ Furnace Oil	21.71	27.64	21.47	28.40	34.44
▨ Coal	7.45	9.49	7.37	9.75	11.82
▨ Natural Gas	12.07	15.37	11.94	15.79	19.15
▨ Heavy Oil	19.83	25.25	19.61	25.94	31.46
▨ Diesel	39.01	49.66	38.58	51.03	61.89

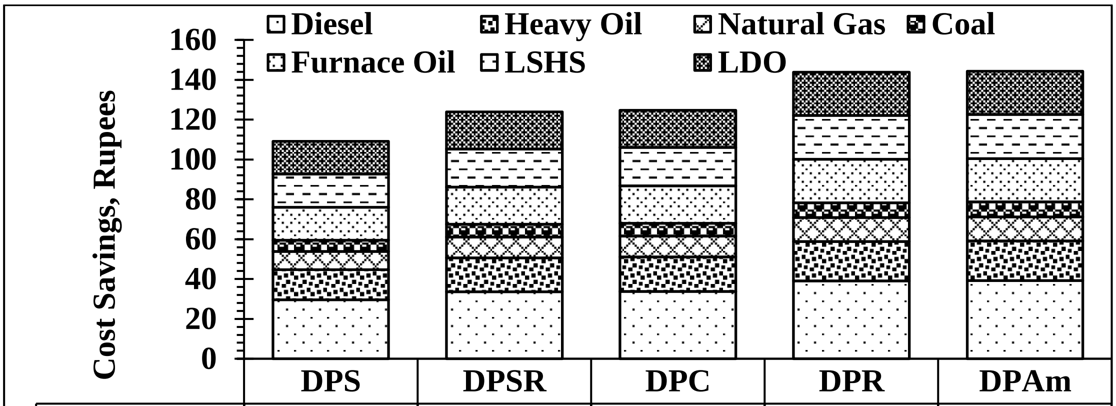
(b)



	GPS	GPSR	GPC	GPR	GPAm
▨ LDO	17.64	23.49	31.41	34.08	25.80
▨ LSHS	18.02	23.99	32.07	34.81	26.35
▨ Furnace Oil	17.71	23.58	31.52	34.21	25.90
▨ Coal	6.08	8.09	10.82	11.74	8.89
▨ Natural Gas	9.85	13.11	17.53	19.02	14.40
▨ Heavy Oil	16.18	21.54	28.80	31.25	23.66
▨ Diesel	31.82	42.37	56.64	61.48	46.54

Asphalt Mixture Type

(c)



	DPS	DPSR	DPC	DPR	DPAm
▨ LDO	16.42	18.62	18.76	21.62	21.71
▨ LSHS	16.77	19.02	19.16	22.07	22.17
▨ Furnace Oil	16.48	18.69	18.83	21.70	21.79
▨ Coal	5.66	6.42	6.46	7.45	7.48
▨ Natural Gas	9.16	10.39	10.47	12.06	12.12
▨ Heavy Oil	15.05	17.07	17.20	19.82	19.91
▨ Diesel	29.61	33.59	33.84	38.99	39.16

Asphalt Mixture Type

(d)

Figure 7.4. Cost savings for WMA mixtures using various fuel type for different groups (a) GVG, (b) DVG, (c) GP, and (d) DP

7.3.2 Maximum Bearable Cost of WMA Additives

Although the application of WMA additives results in substantial cost savings (Figure 7.4) in terms of lower fuel consumption, there is a need to perform a cost-benefit analysis to adjudge whether the cost of additives will offset the obtained cost savings. Marshall mix design was performed for asphalt mixtures considered in this study, and the OBC for different combinations of asphalt binder and aggregate were evaluated. The OBC's are 5.8%, 5.6%, 6%, and 5.9% for GVG, DVG, GP and DP group, respectively. The same values were considered for further calculations. The dosage of each WMA in terms of the weight required to prepare 1000 kg of asphalt mixtures was calculated. For example, 1.35% (by weight of asphalt binder) Sasobit Redux modified asphalt mixtures with granite aggregates at 5.8% OBC requires 58 kg of asphalt binder and 0.783 kg of Sasobit Redux additive to produce 1000 kg of asphalt mixture. A similar approach was used for the other WMA additives except for Aspha-Min. For Aspha-Min based asphalt mixtures, the recommended dosage is 0.3% by weight of asphalt mixture, which is 1000 kg in the present study. Therefore, 3 kg of Aspha-Min additive was used to prepare 1000 kg asphalt mixture, irrespective of aggregate type. Table 7.10 shows the calculated amount of all the WMA additives considered in this research work. Further, the price of the required quantity of WMA additives was calculated based on the unit price of the additives, as shown in the last column of Table 7.10. The unit price of each WMA additive was taken from the manufacturer. Thereafter, the maximum bearable cost of each WMA additive was determined by dividing the cost savings obtained for each fuel type with the weight of the WMA additive required to produce 1000 kg of asphalt mixtures.

In general, the use of WMA will be cost-effective if the maximum bearable cost of the additive is higher than the actual market price. Table 7.11 – Table 7.14 presents the maximum bearable cost per kg for all the WMA additives and different fuel types. It was found that the maximum bearable cost is a function of base asphalt binder, aggregate type and energy source. As can be seen, the maximum bearable cost for heavy oil, natural gas, furnace oil, LSHS, LDO, and coal-based asphalt plants was too low to offset the cost of WMA additives, except DC (Cecabase inclusive asphalt mixture prepared with VG30 and dolomite aggregates). Irrespective of fuel type/energy source, the combination DC, among all the other combinations, showed higher maximum bearable cost of the additive. While comparing different fuel types for DC combination, it was identified that diesel-based asphalt plants provided the highest margin, followed by LSHS, furnace oil, LDO, heavy oil, natural gas, and coal. The findings indicated that the application of Cecabase with VG30 and dolomite aggregates could reduce the energy demand and lower the construction cost when constructed using any fuel (considered in this study). Diesel, the most expensive fuel type, maintained the maximum bearable cost for some other WMA combinations, such as GPC and GPR. Application of GPC indicated some margin in the cost saving, whereas the bearable cost of GPR was found to be approximately the same as actual market price. In addition, the maximum bearable cost obtained for different combinations, such as GC, GR, and DR, in the case of diesel-based asphalt plants, were found to be under 10% range of the actual market price (for the respective WMA additive). Based on the theoretical analysis, it was calculated that the actual market price of all the WMA additives is higher than their respective maximum bearable cost when combined with PMB40 and dolomite aggregates, regardless of the fuel type. This demonstrated that the use of WMA additives in the DP group (where asphalt binder is PMB40 and aggregates are dolomite) may not be cost-effective.

Application of other WMA additives (whose maximum bearable cost is lower than the unit price) combined with different attributes such as aggregate type, base asphalt binder, fuel/energy sources may not be economically viable as it increases the construction cost. It should be noted that, although the construction cost is higher, the importance of mechanical performance and the reduction in GHG emissions must not be ignored for further consideration of these WMA technology for the construction work.

Table 7.10. Required amount and price of WMA additives for 1000 kg asphalt mixtures

WMA Technology	**WMA Additive**	**Unit Price (Rs./kg)**	**Additive Dosage (%)**	**Weight of Additive (kg)**	**Price (Rs.)**
Organic	Sasobit	205	1#	0.58	118.9
			2#	1.16	237.8
			3#	1.74	356.7
	Sasobit Redux	195	0.7#	0.406	79.2
			1.35#	0.783	152.6
			2#	1.16	226.2
Chemical	Cecabase	510	0.2#	0.116	59.2
			0.35#	0.203	103.5
			0.5#	0.29	147.9
	Rediset	475	0.4#	0.232	110.2
			0.5#	0.29	137.7
			0.6#	0.348	165.3
Foaming	Aspha-Min	550	0.3*	3	1650

*Note: # and * represents that the dosage is based on the weight of asphalt binder and weight of asphalt mixture, respectively.*

Table 7.11. Maximum bearable cost for different WMA additives prepared with granite and VG30 based on fuel type

WMA Additive	**Price (Rs.)**	**Max Bearable Cost per kg for Different Fuel Type**						
		Diesel	**Heavy Oil**	**Natural Gas**	**Coal**	**Furnace Oil**	**LSHS**	**LDO**
GS	**356.7**	24.0	12.2	7.4	4.6	13.3	13.6	13.3
GSR	**152.7**	60.1	30.5	18.6	11.5	33.4	34.0	33.3
GC	**147.9**	137.3#	69.8	42.5	26.2	76.4	77.7	76.1
GR	**110.2**	108.5#	55.2	33.6	20.7	60.4	61.4	60.2
GAm	**1650.0**	13.2	6.7	4.1	2.5	7.4	7.5	7.3

**Bearable cost exceeds the market price, #Bearable cost is under 10% range of market price.*

Table 7.12. Maximum bearable cost for different WMA additives prepared with dolomite and VG30 based on fuel type

WMA Additive	**Price (Rs.)**	**Max Bearable Cost per kg for Different Fuel Type**						
		Diesel	**Heavy Oil**	**Natural Gas**	**Coal**	**Furnace Oil**	**LSHS**	**LDO**
DS	**229.6**	34.8	17.7	10.8	6.7	19.4	19.7	19.3
DSR	**147.4**	65.7	33.4	20.3	12.5	36.6	37.2	36.4
DC	**57.1**	344.4*	175.1*	106.6*	65.8*	191.7*	195.0*	191.0*
DR	**159.6**	151.9#	77.2	47.0	29.0	84.5	86.0	84.2
DAm	**1650.0**	20.6	10.5	6.4	3.9	11.5	11.7	11.4

**Bearable cost exceeds the market price, #Bearable cost is under 10% range of market price.*

Table 7.13. Maximum bearable cost for different WMA additives prepared with granite and PMB40 based on fuel type

WMA Additive	**Price (Rs.)**	**Max Bearable Cost per kg for Different Fuel Type**						
		Diesel	**Heavy Oil**	**Natural Gas**	**Coal**	**Furnace Oil**	**LSHS**	**LDO**
GPS	**246.0**	26.5	13.5	8.2	5.1	14.8	15.0	14.7
GPSR	**158.0**	52.3	26.6	16.2	10.0	29.1	29.6	29.0
GPC	**153.0**	188.8*	96.0	58.4	36.1	105.1	106.9	104.7
GPR	**171.0**	170.8*	86.8	52.8	32.6	95.0	96.7	94.7
GPAm	**1650.0**	15.5	7.9	4.8	3.0	8.6	8.8	8.6

**Bearable cost is same or exceeds the market price.*

Table 7.14. Maximum bearable cost for different WMA additives prepared with dolomite and PMB40 based on fuel type

WMA Additive	**Price (Rs.)**	**Max Bearable Cost per kg for Different Fuel Type**						
		Diesel	**Heavy Oil**	**Natural Gas**	**Coal**	**Furnace Oil**	**LSHS**	**LDO**
DPS	**241.9**	25.1	12.8	7.8	4.8	14.0	14.2	13.9
DPSR	**155.3**	42.2	21.4	13.0	8.1	23.5	23.9	23.4
DPC	**150.5**	114.7	58.3	35.5	21.9	63.8	65.0	63.6
DPR	**168.2**	110.1	56.0	34.1	21.0	61.3	62.4	61.1
DPAm	**1650.0**	13.1	6.6	4.0	2.5	7.3	7.4	7.2

7.3.3 Greenhouse Gas Emissions

Since both HMA mixtures (VG30 and PMB40) are prepared at high heating temperatures, it requires a large amount of heat energy, leading to higher environmental impacts. Warm mix technologies, on the other hand, considerably reduced the production temperatures and so the exposure of GHG emissions relative to HMA [91]. Notably, the extent of the environmental impacts (GHG emissions) is also a function of fuel type [10]. Table 7.15 – Table 7.18 presents the emissions in terms of CO_2, CH_4 and N_2O for different asphalt mixtures and fuel types. As can be seen from tables, irrespective of WMA technology, the application of WMA additives exhibited a pronounced reduction in GHG emissions. This is primarily associated with less fuel consumption due to WMA mixtures' reduced production temperature. The obtained values are based on the impact of the GHG (CO_2, CH_4 and N_2O) over the environment. Even though the value of CH_4 and N_2O are relatively lower than CO_2, their impact on the environment is far hazardous than CO_2 [633,655]. To analyze their impact in terms of CO_2, GWP was used to convert the value of GHG emissions resulting from CO_2, CH_4 and N_2O in kgCO_2 equivalent. Figure 7.5 (a-d) shows the overall GHG emissions for all the considered asphalt mixtures prepared using different fuels. As can be seen, natural gas emits lower emissions than diesel, furnace oil, LSHS, LDO, heavy oil and coal. It must be noted that furnace oil and LSHS emit almost the same amount of GHG emissions irrespective of WMA technology. This is due to the similar energy emission factors for both the fuel type. The amount of coal required to produce the asphalt mixture is quite high relative to other selected energy sources, resulting in high GHG emissions. Considering the combination of WMA with different aggregate and asphalt binders analysed in this study, GSR, DAm, GPR, and DPAm showed the highest reduction in GHG emissions, whereas GR, DC, GPS, and DPS combinations indicated the lowest reduction, irrespective of fuel type. It was identified that the extent of reduction in GHG emissions is highly dependent on the aggregate source, type of base asphalt binder and WMA additives. Overall, the calculations indicated that the application of WMA additives, irrespective of aggregate source and base asphalt binder, reduces the GHG emissions as compared to conventional HMA mixtures and thereby facilitate infrastructure development in a more efficient and cleaner way.

Table 7.15. GHG Emissions for HMA and WMA mixtures prepared with granite and VG30

Asphalt Mixture	**GVG**	**GS**	**GSR**	**GC**	**GR**	**GAm**
GHG	**Diesel**					
CO_2 (kg)	1.29E+01	1.17E+01	1.16E+01	1.18E+01	1.22E+01	1.18E+01
CH_4 (kg)	5.21E-04	4.74E-04	4.68E-04	4.76E-04	4.93E-04	4.76E-04
N_2O (kg)	1.04E-04	9.48E-05	9.36E-05	9.52E-05	9.86E-05	9.53E-05
Heavy Oil						
CO_2 (kg)	1.34E+01	1.22E+01	1.21E+01	1.23E+01	1.27E+01	1.23E+01
CH_4 (kg)	5.21E-04	4.74E-04	4.68E-04	4.76E-04	4.93E-04	4.76E-04
N_2O (kg)	1.04E-04	9.48E-05	9.36E-05	9.52E-05	9.86E-05	9.53E-05
Natural Gas						
CO_2 (kg)	9.95E+00	9.05E+00	8.93E+00	9.09E+00	9.40E+00	9.09E+00
CH_4 (kg)	1.77E-04	1.61E-04	1.59E-04	1.62E-04	1.68E-04	1.62E-04
N_2O (kg)	1.77E-05	1.61E-05	1.59E-05	1.62E-05	1.68E-05	1.62E-05
Coal						
CO_2 (kg)	1.51E+01	1.37E+01	1.36E+01	1.38E+01	1.43E+01	1.38E+01

CH_4 (kg)	1.60E-04	1.45E-04	1.43E-04	1.46E-04	1.51E-04	1.46E-04
N_2O (kg)	2.39E-04	2.18E-04	2.15E-04	2.19E-04	2.26E-04	2.19E-04
Furnace Oil						
CO_2 (kg)	1.29E+01	1.18E+01	1.16E+01	1.18E+01	1.22E+01	1.18E+01
CH_4 (kg)	5.32E-04	4.84E-04	4.78E-04	4.86E-04	5.03E-04	4.86E-04
N_2O (kg)	1.06E-04	9.68E-05	9.55E-05	9.72E-05	1.01E-04	9.72E-05
Low Sulphur Heavy Stock						
CO_2 (kg)	1.29E+01	1.18E+01	1.16E+01	1.18E+01	1.22E+01	1.18E+01
CH_4 (kg)	5.32E-04	4.84E-04	4.78E-04	4.86E-04	5.03E-04	4.86E-04
N_2O (kg)	1.06E-04	9.68E-05	9.55E-05	9.72E-05	1.01E-04	9.72E-05
Light Diesel Oil						
CO_2 (kg)	1.31E+01	1.19E+01	1.18E+01	1.20E+01	1.24E+01	1.20E+01
CH_4 (kg)	5.32E-04	4.84E-04	4.78E-04	4.86E-04	5.03E-04	4.86E-04
N_2O (kg)	1.06E-04	9.68E-05	9.55E-05	9.72E-05	1.01E-04	9.72E-05

Table 7.16. GHG Emissions for HMA and WMA mixtures prepared with dolomite and VG30

Asphalt Mixture	**DVG**	**DS**	**DSR**	**DC**	**DR**	**DAm**
GHG	**Diesel**					
CO_2 (kg)	1.33E+01	1.22E+01	1.19E+01	1.23E+01	1.19E+01	1.16E+01
CH_4 (kg)	5.40E-04	4.96E-04	4.83E-04	4.96E-04	4.82E-04	4.70E-04
N_2O (kg)	1.08E-04	9.91E-05	9.67E-05	9.92E-05	9.64E-05	9.39E-05
Heavy Oil						
CO_2 (kg)	1.39E+01	1.28E+01	1.25E+01	1.28E+01	1.24E+01	1.21E+01

CH_4 (kg)	5.40E-04	4.96E-04	4.83E-04	4.96E-04	4.82E-04	4.70E-04
N_2O (kg)	1.08E-04	9.91E-05	9.67E-05	9.92E-05	9.64E-05	9.39E-05
Natural Gas						
CO_2 (kg)	1.03E+01	9.46E+00	9.23E+00	9.46E+00	9.20E+00	8.96E+00
CH_4 (kg)	1.84E-04	1.69E-04	1.64E-04	1.69E-04	1.64E-04	1.60E-04
N_2O (kg)	1.84E-05	1.69E-05	1.64E-05	1.69E-05	1.64E-05	1.60E-05
Coal						
CO_2 (kg)	1.56E+01	1.44E+01	1.40E+01	1.44E+01	1.40E+01	1.36E+01
CH_4 (kg)	1.65E-04	1.52E-04	1.48E-04	1.52E-04	1.48E-04	1.44E-04
N_2O (kg)	2.48E-04	2.28E-04	2.22E-04	2.28E-04	2.21E-04	2.16E-04
Furnace Oil						
CO_2 (kg)	1.34E+01	1.23E+01	1.20E+01	1.23E+01	1.20E+01	1.17E+01
CH_4 (kg)	5.51E-04	5.06E-04	4.93E-04	5.06E-04	4.92E-04	4.79E-04
N_2O (kg)	1.10E-04	1.01E-04	9.87E-05	1.01E-04	9.84E-05	9.58E-05
Low Sulphur Heavy Stock						
CO_2 (kg)	1.34E+01	1.23E+01	1.20E+01	1.23E+01	1.20E+01	1.17E+01
CH_4 (kg)	5.51E-04	5.06E-04	4.93E-04	5.06E-04	4.92E-04	4.79E-04
N_2O (kg)	1.10E-04	1.01E-04	9.87E-05	1.01E-04	9.84E-05	9.58E-05
Light Diesel Oil						
CO_2 (kg)	1.36E+01	1.25E+01	1.22E+01	1.25E+01	1.21E+01	1.18E+01
CH_4 (kg)	5.51E-04	5.06E-04	4.93E-04	5.06E-04	4.92E-04	4.79E-04
N_2O (kg)	1.10E-04	1.01E-04	9.87E-05	1.01E-04	9.84E-05	9.58E-05

Table 7.17. GHG Emissions for HMA and WMA mixtures prepared with granite and PMB40

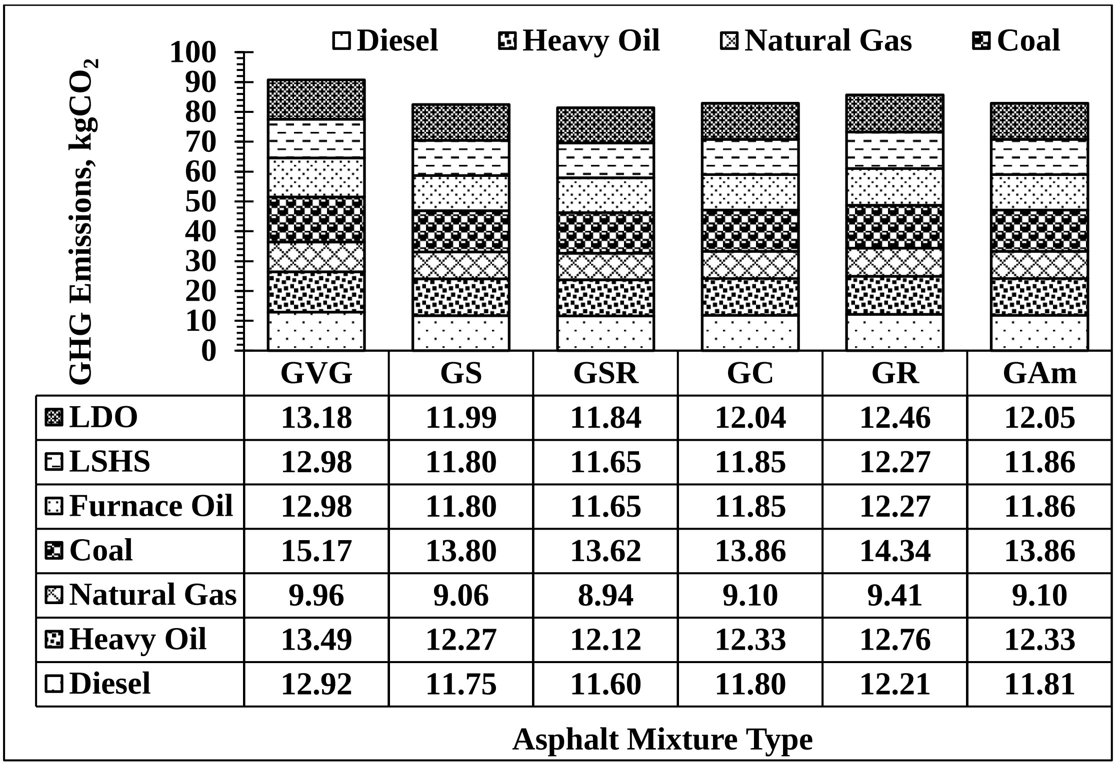
Asphalt Mixture	**GP**	**GPS**	**GPSR**	**GPC**	**GPR**	**GPAm**
GHG	**Diesel**					
CO_2 (kg)	1.37E+01	1.29E+01	1.26E+01	1.22E+01	1.20E+01	1.24E+01
CH_4 (kg)	5.57E-04	5.21E-04	5.09E-04	4.93E-04	4.87E-04	5.04E-04
N_2O (kg)	1.11E-04	1.04E-04	1.02E-04	9.85E-05	9.74E-05	1.01E-04
Heavy Oil						
CO_2 (kg)	1.44E+01	1.34E+01	1.31E+01	1.27E+01	1.26E+01	1.30E+01
CH_4 (kg)	5.57E-04	5.21E-04	5.09E-04	4.93E-04	4.87E-04	5.04E-04
N_2O (kg)	1.11E-04	1.04E-04	1.02E-04	9.85E-05	9.74E-05	1.01E-04
Natural Gas						
CO_2 (kg)	1.06E+01	9.94E+00	9.71E+00	9.40E+00	9.30E+00	9.62E+00
CH_4 (kg)	1.89E-04	1.77E-04	1.73E-04	1.68E-04	1.66E-04	1.71E-04
N_2O (kg)	1.89E-05	1.77E-05	1.73E-05	1.68E-05	1.66E-05	1.71E-05
Coal						
CO_2 (kg)	1.61E+01	1.51E+01	1.47E+01	1.43E+01	1.41E+01	1.46E+01
CH_4 (kg)	1.70E-04	1.59E-04	1.56E-04	1.51E-04	1.49E-04	1.54E-04
N_2O (kg)	2.56E-04	2.39E-04	2.34E-04	2.26E-04	2.24E-04	2.31E-04
Furnace Oil						
CO_2 (kg)	1.38E+01	1.29E+01	1.26E+01	1.22E+01	1.21E+01	1.25E+01
CH_4 (kg)	5.68E-04	5.31E-04	5.19E-04	5.03E-04	4.97E-04	5.14E-04
N_2O (kg)	1.14E-04	1.06E-04	1.04E-04	1.01E-04	9.94E-05	1.03E-04

Low Sulphur Heavy Stock						
CO_2 (kg)	1.38E+01	1.29E+01	1.26E+01	1.22E+01	1.21E+01	1.25E+01
CH_4 (kg)	5.68E-04	5.31E-04	5.19E-04	5.03E-04	4.97E-04	5.14E-04
N_2O (kg)	1.14E-04	1.06E-04	1.04E-04	1.01E-04	9.94E-05	1.03E-04
Light Diesel Oil						
CO_2 (kg)	1.40E+01	1.31E+01	1.28E+01	1.24E+01	1.23E+01	1.27E+01
CH_4 (kg)	5.68E-04	5.31E-04	5.19E-04	5.03E-04	4.97E-04	5.14E-04
N_2O (kg)	1.14E-04	1.06E-04	1.04E-04	1.01E-04	9.94E-05	1.03E-04

Table 7.18. GHG Emissions for HMA and WMA mixtures prepared with dolomite and PMB40

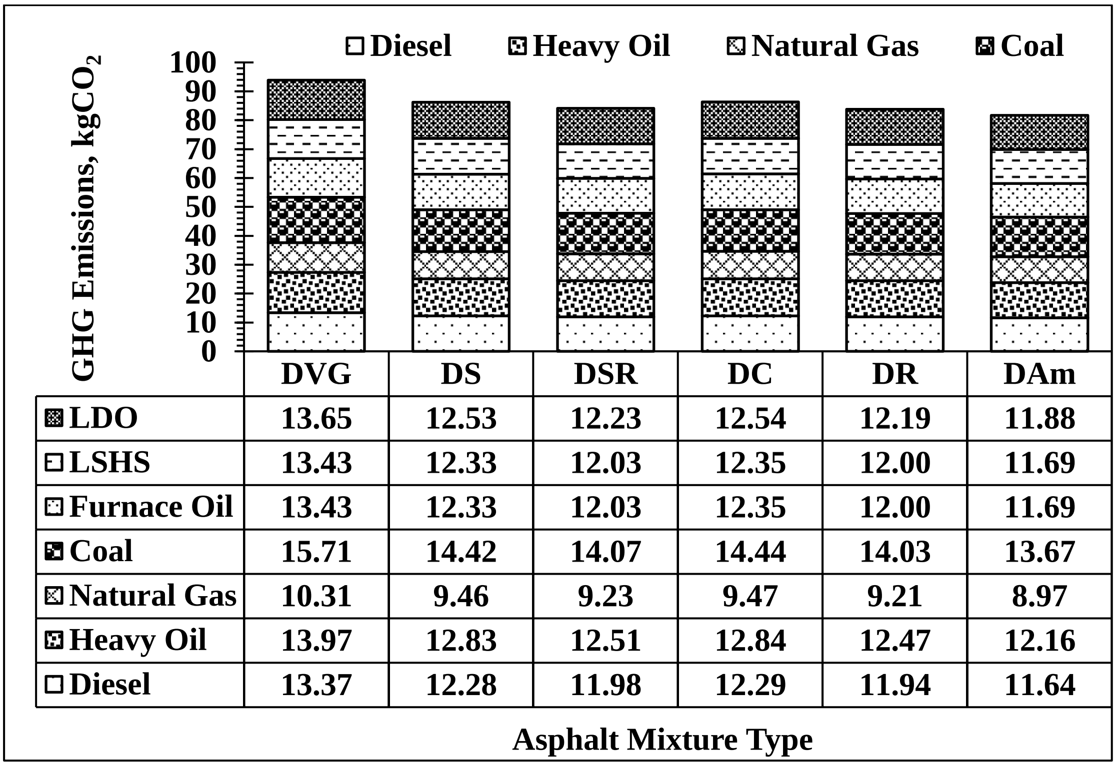
Asphalt Mixture	**DP**	**DPS**	**DPSR**	**DPC**	**DPR**	**DPAm**
GHG	**Diesel**					
CO_2 (kg)	1.42E+01	1.34E+01	1.33E+01	1.33E+01	1.31E+01	1.31E+01
CH_4 (kg)	5.76E-04	5.42E-04	5.38E-04	5.37E-04	5.31E-04	5.31E-04
N_2O (kg)	1.15E-04	1.08E-04	1.08E-04	1.07E-04	1.06E-04	1.06E-04
Heavy Oil						
CO_2 (kg)	1.48E+01	1.40E+01	1.39E+01	1.39E+01	1.37E+01	1.37E+01
CH_4 (kg)	5.76E-04	5.42E-04	5.38E-04	5.37E-04	5.31E-04	5.31E-04
N_2O (kg)	1.15E-04	1.08E-04	1.08E-04	1.07E-04	1.06E-04	1.06E-04
Natural Gas						
CO_2 (kg)	1.10E+01	1.03E+01	1.03E+01	1.03E+01	1.01E+01	1.01E+01
CH_4 (kg)	1.96E-04	1.84E-04	1.83E-04	1.83E-04	1.81E-04	1.81E-04
N_2O (kg)	1.96E-05	1.84E-05	1.83E-05	1.83E-05	1.81E-05	1.81E-05

Coal						
CO_2 (kg)	1.67E+01	1.57E+01	1.56E+01	1.56E+01	1.54E+01	1.54E+01
CH_4 (kg)	1.76E-04	1.66E-04	1.65E-04	1.64E-04	1.63E-04	1.63E-04
N_2O (kg)	2.64E-04	2.49E-04	2.47E-04	2.47E-04	2.44E-04	2.44E-04
Furnace Oil						
CO_2 (kg)	1.43E+01	1.34E+01	1.33E+01	1.33E+01	1.32E+01	1.32E+01
CH_4 (kg)	5.87E-04	5.53E-04	5.49E-04	5.48E-04	5.42E-04	5.42E-04
N_2O (kg)	1.17E-04	1.11E-04	1.10E-04	1.10E-04	1.08E-04	1.08E-04
Low Sulphur Heavy Stock						
CO_2 (kg)	1.43E+01	1.34E+01	1.33E+01	1.33E+01	1.32E+01	1.32E+01
CH_4 (kg)	5.87E-04	5.53E-04	5.49E-04	5.48E-04	5.42E-04	5.42E-04
N_2O (kg)	1.17E-04	1.11E-04	1.10E-04	1.10E-04	1.08E-04	1.08E-04
Light Diesel Oil						
CO_2 (kg)	1.45E+01	1.37E+01	1.35E+01	1.35E+01	1.34E+01	1.34E+01
CH_4 (kg)	5.87E-04	5.53E-04	5.49E-04	5.48E-04	5.42E-04	5.42E-04
N_2O (kg)	1.17E-04	1.11E-04	1.10E-04	1.10E-04	1.08E-04	1.08E-04



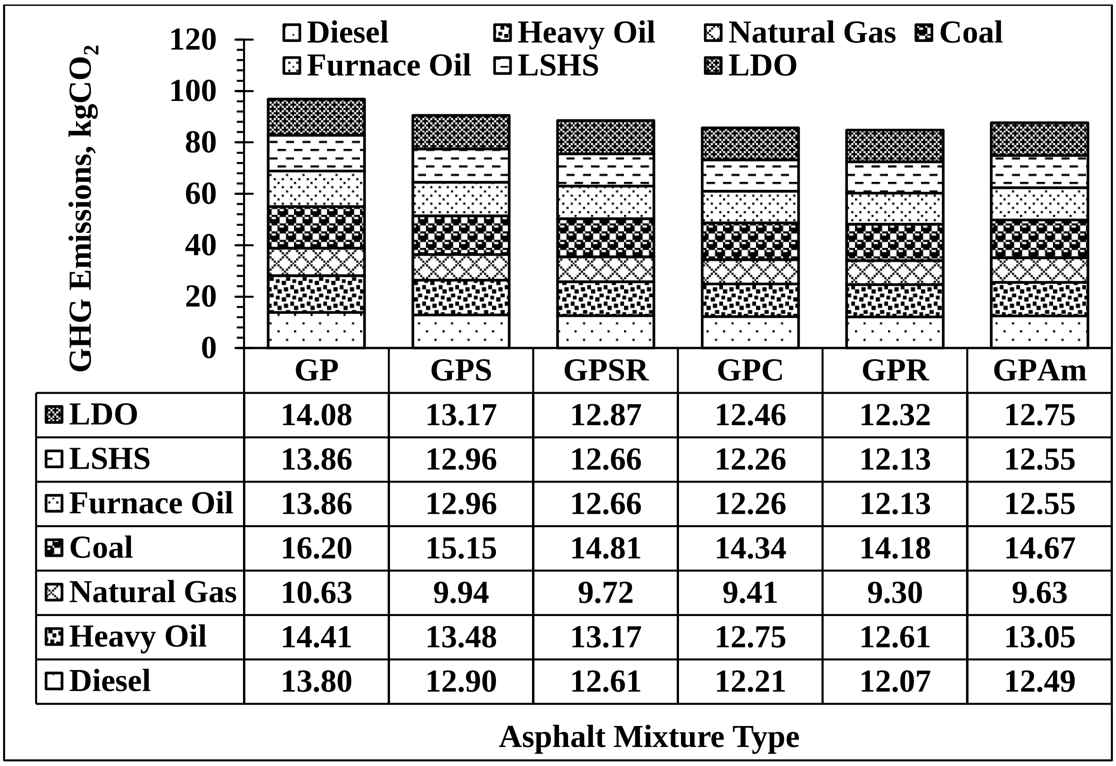
	GVG	GS	GSR	GC	GR	GAm
▩ LDO	13.18	11.99	11.84	12.04	12.46	12.05
☐ LSHS	12.98	11.80	11.65	11.85	12.27	11.86
☐ Furnace Oil	12.98	11.80	11.65	11.85	12.27	11.86
▨ Coal	15.17	13.80	13.62	13.86	14.34	13.86
▨ Natural Gas	9.96	9.06	8.94	9.10	9.41	9.10
▨ Heavy Oil	13.49	12.27	12.12	12.33	12.76	12.33
☐ Diesel	12.92	11.75	11.60	11.80	12.21	11.81

(a)



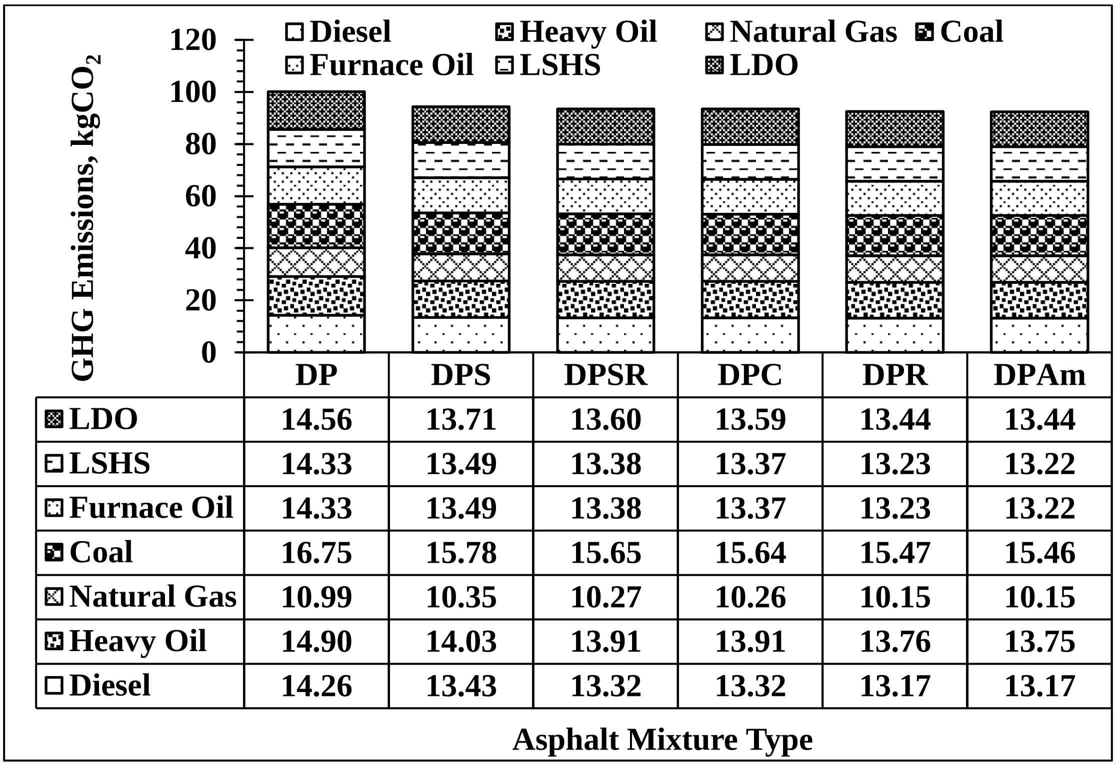
	DVG	DS	DSR	DC	DR	DAm
▩ LDO	13.65	12.53	12.23	12.54	12.19	11.88
☐ LSHS	13.43	12.33	12.03	12.35	12.00	11.69
☐ Furnace Oil	13.43	12.33	12.03	12.35	12.00	11.69
▨ Coal	15.71	14.42	14.07	14.44	14.03	13.67
▨ Natural Gas	10.31	9.46	9.23	9.47	9.21	8.97
▨ Heavy Oil	13.97	12.83	12.51	12.84	12.47	12.16
☐ Diesel	13.37	12.28	11.98	12.29	11.94	11.64

(b)



	GP	GPS	GPSR	GPC	GPR	GPAm
LDO	14.08	13.17	12.87	12.46	12.32	12.75
LSHS	13.86	12.96	12.66	12.26	12.13	12.55
Furnace Oil	13.86	12.96	12.66	12.26	12.13	12.55
Coal	16.20	15.15	14.81	14.34	14.18	14.67
Natural Gas	10.63	9.94	9.72	9.41	9.30	9.63
Heavy Oil	14.41	13.48	13.17	12.75	12.61	13.05
Diesel	13.80	12.90	12.61	12.21	12.07	12.49

(c)



	DP	DPS	DPSR	DPC	DPR	DPAm
LDO	14.56	13.71	13.60	13.59	13.44	13.44
LSHS	14.33	13.49	13.38	13.37	13.23	13.22
Furnace Oil	14.33	13.49	13.38	13.37	13.23	13.22
Coal	16.75	15.78	15.65	15.64	15.47	15.46
Natural Gas	10.99	10.35	10.27	10.26	10.15	10.15
Heavy Oil	14.90	14.03	13.91	13.91	13.76	13.75
Diesel	14.26	13.43	13.32	13.32	13.17	13.17

(d)

Figure 7.5. Total GHG emissions in kgCO$_2$ for HMA and WMA mixtures prepared using different combinations of aggregate and asphalt binder (a) GVG, (b) DVG, (c) GP, and (d) DP

Table 7.19 shows a comparative analysis of benefits that arise by changing the fuel type to produce asphalt mixtures, irrespective of WMA technology, aggregate source, and base asphalt binder. The percent change in total equivalent kgCO_2 was evaluated by taking columns and rows of Table 7.19 as the reference and the variables, respectively. As can be seen, changing the fuel from coal to heavy oil or natural gas reduces the GHG emissions by approximately 11% and 35%, respectively. If coal is replaced by diesel, LSHS, furnace oil or LDO, the reduction in GHG emissions is around 13-15%. Similarly, shifting from heavy oil to natural gas improves the environmental burdens by about 26%. In addition, approximately 2-4% reduction in GHG emissions can be attained by utilizing LDO, furnace oil, LSHS or diesel instead of heavy oil. The adaptation of natural gas as a replacement for diesel, furnace oil, LSHS or LDO results in approximately 23-25% lower GHG emissions. It is predicted that LDO can be altered with diesel, natural gas, furnace oil or LSHS as the latter fuel types provide significant environmental benefits compared to LDO. Overall, natural gas yields lower GHG emissions and is the cleanest energy source than other considered energy sources. On the other hand, coal appear to be the worst fuel type with relatively higher GHG emissions for generating the same heat as other sources.

Table 7.19. Improvement in environmental burden in terms of GHG emission

Energy Source	**Coal**	**Heavy Oil**	**Diesel**	**Natural Gas**	**Furnace Oil**	**LSHS**	**LDO**
Coal	**0.0**	**11.1**	**14.8**	**34.4**	**14.5**	**14.5**	**13.1**
Heavy Oil	-12.4	**0.0**	**4.2**	**26.2**	**3.8**	**3.8**	**2.3**
Diesel	-17.4	-4.4	**0.0**	**22.9**	-0.4	-0.4	-2.0
Natural Gas	-52.4	-35.5	-29.8	**0.0**	-30.3	-30.3	-32.4

Furnace Oil	-16.9	-4.0	**0.4**	**23.3**	**0.0**	**0.0**	-1.6
LSHS	-16.9	-4.0	**0.4**	**23.3**	**0.0**	**0.0**	-1.6
LDO	-15.1	-2.3	**2.0**	**24.5**	**1.6**	**1.6**	**0.0**

Note: For energy sources, fuel type in columns are the reference and fuel types in rows are the variables. Boldness indicates the improvement in GHG emissions, and the values are in percentage.

7.4 Summary

The production of conventional HMA mixtures is an energy-intensive process that brought drastic changes in the environment due to elevated heating temperatures. The energy consumption at high temperatures directly impacts the construction cost of the pavement. Thus, the production of HMA mixture increases the environmental burdens and accelerates the economic concerns. To counteract such concerns, the implementation of WMA technology can be one of the prominent solutions. Various WMA additives were developed and utilized to replace conventional HMA mixtures. The economic and environmental benefits derived from WMA technologies are associated with reducing the amount of energy consumption and GHG emissions during the manufacturing of asphalt mixtures.

The present study investigated the amount of energy consumption and resulting exposure to GHG emissions during the production of asphalt mixtures, especially for WMA technologies with different combinations of aggregate and base asphalt binder. This study is a distinct departure from the previous studies in the way that it analyzed different WMA mixtures using various fuel types/energy sources. The conclusions drawn from this assessment are as follows:

- Almost 60% of heat energy was found to be consumed in heating the aggregate, followed by water vaporization (25%), heating asphalt binder (10%), heating water (4%), and removal of steam (1%). Reduction in heat energy with the addition of WMA additives ranges from 5-13% relative to conventional HMA mixtures (VG30 and PMB40). The extent of reduction for a particular WMA technology is a function of aggregate source and base asphalt binder.
- The overall cost of producing asphalt mixtures using coal was considerably lower, whereas the amount of coal required to generate a fixed quantity of heat energy was approximately 1.73, 1.28, 1.26, 1.25, and 1.21 for natural gas, furnace oil and LSHS, diesel, heavy oil, and LDO, respectively. The application of Rediset and Cecabase with granite and dolomite aggregates, respectively, in VG30 resulted in the lowest cost reduction, whereas in PMB40, the incorporation of Sasobit with any aggregate type, showed lowest cost savings, irrespective of fuel type.
- The maximum bearable cost for heavy oil, natural gas, furnace oil, LSHS, LDO, and coal-based asphalt plants was too low to offset the cost of WMA additives, except DC, on the other hand, diesel maintained the maximum bearable cost for GPC and GPR. Preparation of asphalt mixtures with the use of WMA additives in DP group may not be cost effective, regardless of fuel type considered in the study.
- The implementation of WMA technologies exhibited a pronounced reduction in GHG emissions relative to conventional HMA. The production of GSR, DAm, GPR, and DPAm released lower emissions, irrespective of fuel type. The extent of reduction in production temperatures of WMA mixtures proportionately influenced the quantity of reduced emissions.
- GHG emissions can also be minimized by adopting a cleaner energy source. Natural gas emits lower emissions, whereas coal leads to negative environmental impact.

Shifting from coal, heavy oil, LDO, furnace oil, LSHS and diesel-based plants to natural gas reduced the environmental burden by a considerable amount ranging from 23-35%.