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Estimation and Analysis of Energy Conservation and Emissions Reduction Effects of Warm-Mix Crumb Rubber-Modified Asphalts during Construction Period

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Abstract: In order to solve the serious environmental problems caused by the rapid increase in the number of waste tires and unproper storage of waste tires, modifying the asphalt mix for roadway pavement by adding rubber crumb from recycled waste tires is one of the highly effective approach to solve the problem and can achieve the sustainable use of rubber resources. The application of warm-mix crumb rubber-modified asphalt (CRMA) overcomes some issues of the hot-mix CRMA, such as high temperature and high energy consumption. However, there is a lack of estimation methodology for the energy conservation and emission reduction during the production process of warm-mix CRMA. This study develops the estimation models for the evaluation of energy conservation and emissions reduction during different production stages of waste rubber powder, asphalt, CRMA, hot-mix CRMA, and warm-mix CRMA. A list for gas emissions during the mixing and paving process of CRMA mixtures was established through the simulated mixing measurement and paving site measurement. The results show that for each metric ton of CRMA mixture produced, warm mixing can reduce energy consumption by 18~36% and decrease gas emissions during different stages by 15~87% compared to hot mixing. The Evotherm warm-mix CRMA mixture with DAT as warm mix agent (Ev-DAT warm-mix CRMA mixture) is more energy-efficient by saving approximately 108.56 MJ of energy and reducing gas emissions during mixing and paving by at least 32% and 73%, respectively. This model can improves the technical standard of warm-mix CRMA and the energy conservation assessment.

Keywords: waste rubber powder; crumb rubber-modified asphalt; warm mixing; energy conservation; emissions reduction; estimation

1. Introduction

In 2017, global rubber consumption was 28.277 million tons, of which China's rubber consumption was 9.432 million tons. China is the world's largest consumer of rubber and the second-largest producer of waste tires [1]. It is estimated that 370 million waste tires weighing more than 13.5 million tons was produced in Mainland China in 2017. The country is facing severe disposal problems of waste tires since the output is increasing every year. In China, over 50% of waste tires are discarded without treatment [2,3], which has caused huge waste of resources. Improving the recycling efficiency of waste tires is critical for sustainable development and alleviating the shortage of rubber resources in China.

Currently, most waste tires are treated as solid waste and are burned or dumped in landfills [4]. In 2007, the quantity of waste tires made into tire-derived fuel in the United States exceeded half of their annual tire yield, while the other 17.2% and 12.2% of waste tires were used as ground rubber materials and civil engineering materials respectively [5]. Waste recycling method that utilizes incineration, pyrolysis, and gasification are generally called waste-to-energy (WTE) processes [6]. This method may not be the best recycling method [7] since it releases a large amount of CO_2, which causes environmental problems and prevents reutilizing rubber resources even though it converts the waste tires into usable heat, electricity, or fuel. Waste tire treatment consumes natural resources and produces environmental pollution, especially improper treatment results in an unacceptable level of natural resource consumption, environmental pollution, and massive carbon dioxide (CO_2) emissions.

For saving rubber resources, realizing waste-tire sustainable utilization, and avoiding new pollutions and CO_2 emissions during recycling, researchers have contributed huge efforts. Bhadra et al. [4] processed waste tires into recycled carbon black, which realized rubber resources recycling utilization. Ayanoğlu and Yumrutaş [8] adopted catalytic distillation for waste-tire pyrolysis to obtain engine fuel. In the field of civil engineering construction, researchers have used waste tires as an additive to enhance the performance of concrete [9]. In road pavement construction, waste-tire rubber can serve as an asphalt modifier after being grinded and purified, which has been proved to be an effective polymer for asphalt modification. The incorporation of rubber powder not only can improve the high temperature rheological performances of rubberized binders [10], but also can enhance CRMA anti-fatigue and anti-cracking performance [11]. Different types of rubber sources and rubber types can be used to modify different types of base asphalt to obtain excellent high temperature rheological properties and short-term aging properties [11]. Comparing the CRMA with the SBS-modified asphalt, CRMA has better water resistance and permanent deformation resistance, and CRMA has better low temperature cracking resistance [12]. A consensus has been reached on research of the modification mechanism of waste rubber powder on asphalt. The interaction between rubber powder and base asphalt is a component exchange process in which no chemical reaction occurs. The addition of wax-based WMA additives promotes the molecular blending of rubber powder with base asphalt, promotes exchange between components, and reduces its own viscosity [13]. The rubber powder specific surface, grinding process and the process parameters of asphalt blending greatly affect the quality of the CRMA, and the above factors can be optimized to obtain high temperature performance and low temperature performance superior CRMA [12]. Therefore, with the excellent performance of CRMA concrete, a considerable amount of CRMA has already been applied to modify asphalt road pavement [14].

CRMA concrete pavement has made outstanding contributions to energy saving and emission reduction in the industry. The improvement of performance can reduce asphalt layer thickness, extend road life, reduce road noise and maintenance costs [15,16]. CRMA can substitute part of asphalt, which saves the cost and quantity of asphalt materials with excellent energy saving capability [17]. However, since the blending of rubber powder and asphalt requires high temperature conditions of 190~200 °C, the mixing temperature of the mixture needs to be 180~185 °C, the emission of CRMA increases and energy consumption increases [13]. In the asphalt production process, the decreases of heating temperature requirements can directly affect the cost and consumption of energy, and can also alleviate the aging caused by heating and improve service life of pavement [18]. Warm mix technology provides a solution to reduce the blending temperature of CRMA. Adding liquid warming catalyst can reduce 5~10 °C of the production temperature of CRMA. Under the lower layer or looser requirements, the production temperature can be reduced by up to 25~30 °C, even at the 40 °C lower production temperature, the moisture–damage strength ratio, rutting resistance and stability of the warm-mixed CRMA are better than the nonadhesive powder hot mix asphalt (170 °C), which will not affect the service life of pavement [19]. The addition of warming catalyst reduces harmful emissions and carbon dioxide (CO_2) emissions [20]. Hot-mix asphalts require temperatures over 160 °C during production to facilitate the rapid oxidation of hydrocarbons [21]. Conventional production of hot-mix

asphalts generally releases large amounts of harmful gases [22–24]. Replacing conventional hot-mixing techniques with warm-mixing techniques can lower the temperatures of production and paving by at least 20 °C. Applying third-generation Evotherm as warming-mix agent to produce warm-mix CRMA can save 5.8% asphalt and 13% fuel consumption and reduce harmful gas emission [25]. The utilization of warm mixing saves 1.61 US dollars for each metric ton of asphalt mixture production and reduces the emissions of CO and CO_2 [26]. The above literatures prove that the warm mixed CRMA has excellent road performance and energy saving ability, however the research results focus on one or several aspects of energy saving and emission reduction, and there is no comprehensive consideration of waste rubber powder production, asphalt production, CRMA production, hot mixed CRMA mixture production, warm mixed CRMA mixture production process in the comprehensive energy saving emission reduction measurement, for comprehensively and objectively evaluate the contribution of energy-saving and emission reduction of warm mixed CRMA.

In recent years, researches on the calculation models and methods of energy saving and emission reduction during the construction period of asphalt pavement have emerged. One research determined the parameters and values of energy saving and emission reduction benefit of warm mixed asphalt technology (WMA), established its energy saving and emission reduction calculation process and measurement model, engineering calculation shows that the production of 1 ton asphalt mixture, comparing to hot mix technology, the CO_2 emission reduction is 29.79% of warm mix asphalt, and the harmful gas emission reduction is reduced by more than 65% [27]. The asphalt concrete pavement construction period is divided into three stages: raw material production, raw material transportation and construction, an environmental calculation model is established to calculate the composition of energy consumption and carbon emissions of typical semi-rigid base asphalt concrete pavements in China, with comparing and analyzing the energy saving and emission reduction of warm mix technology and regeneration technology [28]. Another research determined the system index of greenhouse gas emission evaluation for asphalt pavement construction, and proposed the calculation method and statistical model of the evaluation system index, the energy saving and emission reduction effects were analyzed by determining the asphalt surface layer at different mixing temperatures and the greenhouse gas emissions during the construction of cement and cement-free substrates [29]. In this study, the whole process of rubber asphalt from the production of raw materials to the construction of rubber asphalt mixture is considered as the calculation object. The calculation model draws on the thermodynamic equations in the above literatures, and revises the energy saving benefit of waste rubber powder substituting asphalt. The special measurement of CRMA mixing, energy consumption and harmful gas emissions during construction, established an energy consumption model considering the actual heat exchange rate, and improved the lack of comprehensive comparison of energy saving and emission reduction effects of different rubber asphalt warming agents in relevant literatures, realized more accurate energy-saving emission reduction calculation of warm mixed rubber modified asphalt mixture, which can be used as the decision-making basis for decision makers to choose different warming agent.

The main work of this paper is as follow: Section 2 introduces the measurement method of gas emission and energy consumption; Section 3 covers the properties of experimental materials; Section 4 introduces the process of measuring the energy conservation and emission reduction benefits of CRMA; Section 5 elaborates the process of measuring the energy conservation and emission reduction benefits of different warm-mix asphalt versus hot-mix asphalt; Section 6 draws the conclusion.

2. Methodology

This research is devoted to the energy conservation of emission reduction benefits of warm-mix CRMA and has carried out a series of measurements on energy consumption and gas emissions. In the production of CRMA, different kinds of harmful gases are generated due to the heating of asphalt and rubber during mixing and paving. Different gas detection devices are used to sample and measure the gases during mixing and paving process. Emission reduction effects is

obtained of different warm-mix CRMAs by comparing with hot-mix CRMA. The production of CRMA included three stages, production, transportation, and paving. For the CRMA with different warm-mix agents, the energy consumption during transportation and paving is the same with identical means of transportation and paving equipment. In the production process, the discharge and mixing temperature are different due to different cooling effects of different warm-mix agents. The test specimens are made by a Superpave Gyratory Compactor (SGC). The relationship between void ratio and molding temperature was measured and mixing and paving temperature were determined. A model based on the thermodynamic equation and considering the actual heat exchange rate was established to measure the energy consumption. The energy consumption of CRMA with different warm-mix agents was measured and finally the energy consumption was compared with the energy consumption of hot-mix CRMA.

2.1. SGC Test Specimens

Sample mixing and paving temperature was determined by the Superpave design method. The SGC test parameters were rotation angle of 1.16° ± 0.02°, vertical pressure of 600 kPa ± 18 kPa, rotation rate of 30 r/min ± 0.5 r/min. The specimen is cylindrical with a 150-mm diameter. The indenter needs to be heated and kept for more than 15 min before rotary compaction. The test specimens were placed in an oven at 150 °C ± 5 °C for over 45 min before the test start. The inner rotation angle measuring devices do not need to be heated.

2.2. Measurement of Gas Emissions

As shown in Table 1, several measurement devices, including gas detector, GS-IIIB atmospheric sampler, asphalt fumes sampling detector, and gas chromatograph were used to measure harmful gases and fumes. The measurements of gas emissions generated during the mixing process of asphalt mixtures were conducted through laboratory simulated mixing production since they are sensitive to external factors. The mixing process was simulated in a mixing tank, and the gases inside the cylinder were detected using a gas detector directly when mixing was completed. The gas emissions generated during paving process were measured at the construction site. GS-IIIB atmospheric sampler was used to collect and detect the asphalt fume and harmful gases generated during the paving process. Gas chromatograph was used to detect the concentration of Benzopyrene in the asphalt fume. And the concentration of benzene solubles was measured using Soxhlet extraction gravimetric method.

Table 1. Test equipment and function.

Measurement Devices	Production Stage	Function
GS-IIIB atmospheric sampler	Mixing and Paving	Gases Collection
gas detector	Mixing and Paving	Detection of CO_2 CH_4 N_2O SO_2 CO NO_X
dust sampler	Mixing and Paving	Dust Collection
asphalt fumes sampling detector	Paving	Detection of Asphalt Fumes
gas chromatograph	Paving	Detection of Benzopyrene

The type and quantity of harmful gases released varies with different mixing techniques and temperature. The gas emissions during the mixing and paving process of four warm-mix CRMAs were measured and analyzed, then the results were compared with those of a hot-mix CRMA to determine the benefits of warm mixing in terms of emissions reduction.

2.3. Estimation Method of Energy Conservation Benefits

The temperature requirements of hot-mix CRMA differ from those of warm-mix CRMA. Therefore, although the energy consumption of these two types of CRMA are identical in terms of transportation and paving, they differ in terms of heat supply for production. This study calculated and analyzed the differences in heat energy.

The temperatures required during the production stages of each CRMA mixture was confirmed first before estimating the energy conservation benefits of the different CRMA mixtures. The amount of energy consumed to provide heat for asphalt production is mainly determined by the mixing temperature required during each production stage, the mixture formulas, the specific heat capacity of the aggregates, and the water content of the aggregates. Based on these factors and relevant parameters, the theoretical amount of energy conserved per unit of mixture can be calculated when warm mixing is used.

The estimation model for energy savings is

$$E = E_H - E_W \tag{1}$$

where E denotes the amount of energy conserved by the warm-mix CRMA mixture; and E_H and E_W indicate the amount of energy consumed by the hot-mix CRMA mixture and the warm-mix CRMA mixture respectively.

The theoretical amounts of energy consumption can be calculated using thermodynamics formulas. The temperatures required during different stages of warm mixing, such as asphalt discharge temperature, aggregate discharge temperature, and mixing temperature, are lower than those of hot mixing, which means lower energy consumption. The theoretical amount of energy consumed during different warm-mixing processes can be calculated using Equation (2):

$$Q_T = \sum_{i=1}^{3} C_i M_i \Delta t_i \tag{2}$$

where Q_r is the theoretical amount of energy consumed ($J \cdot kg^{-1}$); C_i represents the specific heat capacity of the CRMA mixture during state i ($J \cdot (kg \cdot °C)^{-1}$); M_i denotes the weight of the CRMA mixture during stage i (kg); and $\triangle t_i$ is the production temperature difference during stage i (°C) (i = 1, 2, 3).

As for aggregate heating, the burning efficiency of the fuel and the heat exchange rate of the heating roller must be taken into consideration. The amount of energy consumed to heat the aggregates can be calculated using Equation (3):

$$Q_A = Q_T / W_B / R_H \tag{3}$$

where Q_A is the actual amount of energy consumed to heat the aggregates; W_B denotes the burning efficiency of the fuel; and R_H represents the heat exchange rate of the heating roller.

For the heating of water, it is necessary to consider the energy required for heating and the latent heat required for phase change.

$$Q_W = M_W \Delta t_W C_W + M_W \Delta t_W C_{LH} + M_W \Delta t_W C_v \tag{4}$$

where Q_W is the energy consumed to heat the water; M_W is the mass of liquid water; Δt_W is the temperature difference of liquid water; C_W is the specific heat capacity of liquid water; C_{LH} is the latent heat required for the phase change of water; C_v is the specific heat capacity of water vapor.

For the heating of materials other than the aggregate (including the asphalt, rubber powder, and warm-mix agent), only the burning efficiency needs to be considered for the actual amount of energy consumed, which can be calculated using Equation (5):

$$Q_M = \frac{Q_T}{W_B} \tag{5}$$

where Q_M is the actual amount of energy consumed to heat the materials aside from the aggregate.

The actual amount of energy consumed is the total amount of energy required to heat all of the raw materials, which can be calculated using Equation (6):

$$Q_P = Q_A + Q_M \tag{6}$$

where Q_P denotes the actual amount of energy required for heating.

3. Experiment Materials and Mixture Properties

Chinese-manufactured SK90# was served as the matrix asphalt of the CRMAs. The properties of SK90# are shown in Table 2. The 60-mesh rubber powder, which meet all the requirements of the Technical Specifications for Construction of Highway Asphalt Pavement (JTG F40-2004), is adopted for this experiment. The physical and chemical properties of 60-mesh rubber powder are listed in Table 3. Four types of warm-mix agents, Sasobit, DAT, TOR, and Aspha-Min were chosen, and their properties are exhibited in Table 4.

Table 2. Technical properties of SK90# asphalt.

Item		Measured Value	Technical Requirement	Test Method
Penetration (25 °C, 100 g, 5 s)/0.1 mm		92	80~100	T0604
Penetration index (PI)		0.98	−1.0~+1.0	T0604
Ductility (10 °C)/cm		>100	≥45	T0605
Softening point (ring and ball method)/(Pa·s)		46.5	≥45	T0606
Kinematic viscosity (60 °C)/(mPa·s)		171	≥160	T0620
Density (15 °C)/(g·cm^{-3})		0.983	Measured value	T0603
Residue after TFOT	Change in weight/%	−0.29	≤±0.8	T0609
	Retained penetration (25 °C)/%	69.6	≥57	T0604

Table 3. Physical and chemical properties of 60-mesh rubber powder.

Tested Items	Measured Value	Technical Requirement
Relative density/(g·cm^{-3})	1.123	1.10~1.30
Water content/%	0.08	<1.00
Metal content/%	0	<0.01
Fiber content/%	0.01	<0.05
Natural rubber content/%	77	≥40
Acetone extract/%	9.2	6~16
Carbon black content/%	31	28~38
Rubber hydrocarbon content/%	68	≥42

Table 4. Properties of warm-mix agents.

Warm-Mix Agent	Substance Classification	Chemical Composition	Mixing Techniques
Sasobit	Paraffin	Polyolefin	Mix with organic warm mix agent
DAT	Soap liquid	Organic nitride	Emulsification
TOR	Trans-polyoctenamer rubber reactive modifier	Octene polymer	Mix with Evotherm (chemical warm mix agent)
Aspha-Min	Zeolite	Aluminate mineral	Foaming

Experiments were conducted based on the penetration, the softening point, ductility, elastic recovery, and rotation difficulty to determine the optimal mixing amounts of Sasobit, DAT, TOR, and Aspha-Min which were 3% of the matrix asphalt weight, 0.7% of the CRMA weight, 4.5% of the

rubber powder weight, and 0.3% of the mixture weight, respectively. The rubber powder content of the CRMA was 22%.

Basalt is used for both the fine and coarse aggregates and limestone powder is adopted for the filler. Gap grading is more suitable for CRMAs based on experience. AR-SMA-13 grading was adopted for the mixtures in this experiment and the optimal bitumen-aggregate ratios was determined using the Marshall test method. The design porosity was 4.5%. The bitumen-aggregate ratios derived for the asphalt mixtures are shown in Table 5.

Table 5. Pavement performance properties of asphalt mixtures.

Road Performance Property	Design Porosity (%)	Bitumen-Aggregate Ratio (%)	Dynamic Stability (frequency/mm)	Maximum Bending Strain (με)	Freeze-Thaw Splitting Strength (%)
Matrix asphalt mixture	4.5	6.0	1042.1	2456.7	78.5
Hot-mix CRMA mixture	4.5	7.0	4313.4	3164.2	84.3
Sa warm-mix CRMA mixture	4.5	6.8	8560.3	3124.6	81.3
Ev-DAT warm-mix CRMA mixture	4.5	7.0	4989.7	3341.3	83.8
TOR warm-mix CRMA mixture	4.5	7.0	4691.3	4211.6	87.0
Asp warm-mix CRMA mixture	4.5	6.3	4017.2	3246.1	88.6
Technical requirement (JTG D50-2017)	-	-	≥3000	≥2500	≥80

Note: Sa warm-mix CRMA mixture is the warm-mix CRMA mixture with Sasobit as warm mix agent, TOR warm-mix CRMA mixture is the warm-mix CRMA mixture with TOR as warm mix agent, Asp warm-mix CRMA mixture is the warm-mix CRMA mixture with Aspha-Min as warm mix agent.

To assess the common pavement performance properties of the matrix asphalt mixture, hot-mix CRMA, and the four warm-mix CRMAs, high-temperature rutting tests, low-temperature bending tests, the Marshall Immersion test, and freeze-thaw splitting tests were conducted to the six asphalt mixtures. Table 5 summarizes all the test results. All the asphalt mixtures met the requirements of the Specifications for Design of Highway Asphalt Pavement (JTG D50-2017).

4. Estimation of Energy Conservation and Emissions Reduction of CRMAs

The energy consumption of waste rubber powder production by different methods was investigated. Energy consumption and emission of rubber and asphalt production were obtained through the tests of the decompression device and the propane deasphalting device for energy consumption and emission during the asphalt pavement production. The conserved energy and reduced emission due to the use of rubber powder as a modifier can be calculated using formulas at the rubber powder content of 22%. In this study, the energy consumption of producing one metric ton rubber powder is 2286 MJ, while the energy consumed per metric of asphalt production in China is 2930 to 4061 MJ. The energy consumption of rubber powder production is approximately 55% to 77% of that of asphalt production.

4.1. Production Process of Rubber Powder and Its Energy Consumption

The most common methods of producing waste-tire rubber powder are ambient-temperature grinding and cryogenic grinding. Grinding at ambient temperature involves the use of equipment such as a grinding machine and a shredding machine to crush, grind, cut, and tear the rubber. The grinding temperature is approximately 50 °C and the rubber is flexible at such temperature. Ambient-temperature grinding includes dry and wet processes. The former technique involves bead wire removal, shredding, granulating, grinding, and magnetic separation, as shown in Figure 1, while the latter technique is referred to as solution grinding, which waste rubber is grinded into rubber powder in water or an organic solvent. The RAPRA method (the method developed by the Association Rubber and Plastics Research Association of Great Britain [RAPRA]) is the most representative method of solution grinding. With wet grinding, the particle size of the rubber powder can be controlled to

between 0.3 μm and 5 μm, which is smaller than that produced by dry grinding and the rubber also absorbs less heat, in which lead to the rubber powder with better properties.

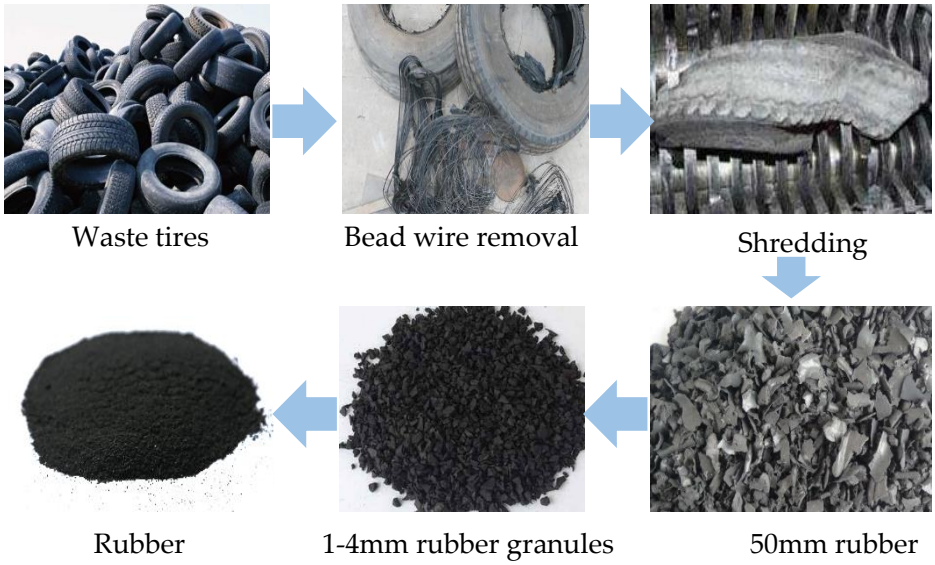


Figure 1. Dry process of rubber powder production.

For cryogenic grinding, the low temperatures embrittle the waste rubber before it is grinded. The rubber powder obtained from this method is generally between 50 mesh to 200 mesh. Cryogenic grinding includes conventional cryogenic grinding, in which low temperatures are applied throughout the process, and ambient temperature-cryogenic grinding with liquid nitrogen.

The energy consumption and economic index of one metric ton of rubber powder produced by four different production techniques are shown in Table 6, ambient-temperature grinding is more cost-effective, and the production process is relatively simpler than the cryogenic grinding. Dry method is the most commonly used to produce waste rubber powder.

Table 6. Energy consumption and economic indexes of different fine rubber powder production methods.

Rubber Powder Production Method	Ambient-Temperature Grinding		Cryogenic Grinding	
	Dry	Wet	Conventional Cryogenic Grinding	Ambient Temperature-Cryogenic Grinding with Liquid Nitrogen
Energy consumption (kWh/t)	630	910	1590	1340
Gas consumption (m^3/t)	0	0	55	19
Liquid nitrogen consumption (t/t)	0	0	3.9	1.7
Production cost (USD/t)	178	205	475	395

4.2. Production Process of Asphalt and Its Energy Consumption

The blending method is used to produce asphalt for heavy-traffic roads in China. It involves blending hard components (e.g., deoiled asphalt) and soft components (e.g., asphalt, vacuum residue, and catalytic slurry oil) together to obtain asphalt, the process of which is as shown in Figure 2.

Atmospheric residue is pumped into a vacuum furnace and heated to around 400 °C before being sent into a vacuum tower. The noncondensable gases and steam separated at the top of the tower enters an atmospheric condenser to be cooled, and subsequently, the noncondensable gases are extracted to ensure the degree of vacuum. The side distillates are subjected to stripping and heat-exchange cooling before leaving the vacuum tower. The pressure of the vacuum residue is increased via pumping,

and the vacuum residue exchanges heat with crude oil to recycle the heat. The vacuum residue will be released from vacuum tower after cooling. Then it enters the propane deasphalting unit. If non-critical extraction is adopted when the vacuum residue enters the asphalt separation tower in the propane deasphalting unit, then supercritical recovery will be used when the deasphalted oil solution enters the deasphalted oil separation tower. The deasphalted oil contains propane solvent that is recovered by the flash tower and the stripper. Deoiled asphalt can be obtained at the bottom of the stripper.

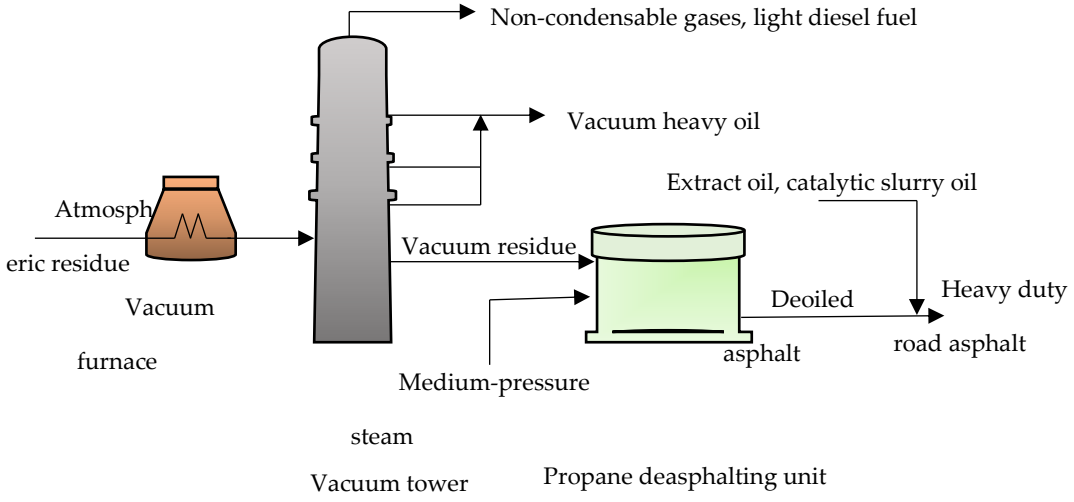


Figure 2. Asphalt production process.

The energy consumed during the operation of the vacuum unit includes the fuel consumed by the furnace, cold stream consumption, steam consumption, and electricity consumption. The total amount of energy consumed by the vacuum unit is calculated using Equation (7):

$$E_{vro} = \frac{\sum_{i=1}^{I} E_{aro,\,i}}{P_S} \tag{7}$$

where E_{vro} is the amount of energy consumed by the vacuum unit in the production of 1 metric ton of vacuum residue; $E_{aro,\,i}$ is the amount of energy consumed in the processing of substance i in 1 metric ton of atmospheric residue, including the fuel consumed by the furnace, cold stream consumption, steam consumption, and electricity consumption; and P_S denotes the residue yield.

The propane deasphalting unit uses a heat transfer oil heater in which the heat load is mainly derived from heat exchange with heat transfer oil. The energy consumed by the operation of the unit includes fuel gas, electricity, and steam and is calculated using Equation (8):

$$E_{ooa} = \frac{\sum_{i=1}^{J} E_{vro,\,j}}{P_{ooa}} \tag{8}$$

where E_{ooa} is the amount of energy consumed in the production of 1 metric ton of de-oiled asphalt; $E_{vro,j}$ is the amount of energy consumed by the propane deasphalting unit in the processing of substance j in 1 metric ton of vacuum residue, and P_{ooa} denotes de-oiled asphalt yield. Depending on the crude oil, P_{ooa} fluctuates between 54% and 69% in China and is set at 65% in this equation.

The energy consumption of the propane deasphalting unit is shown in Table 7.

Table 7. Energy consumption of propane deasphalting unit.

Item	Energy Consumption
Fuel gas (MJ/t)	927.61
1.0 MPa steam (MJ/t)	198.34
Output of self-produced 0.3 MPa steam (MJ/t)	−62.71
Electricity (MJ/t)	412.46
Circulating water (MJ/t)	32.22
Condensate (MJ/t)	−0.98
Total energy consumption (MJ/t)	1506.94

Using Equations (7) and (8), the calculated energy consumption and gas emission of the asphalt production process is shown in Table 8.

Table 8. Energy consumption and gas emissions of asphalt production process.

Vacuum Unit		Propane Deasphalting Unit	
Energy Consumption (MJ/t)	**CO_2 (kg/t)**	**Energy Consumption (MJ/t)**	**CO_2 (kg/t)**
1244.75	28.69	2318.37	13.62

The production of deoiled asphalt requires oil to pass through a vacuum tower and a propane deasphalting unit. The energy consumption of one metric ton of deoiled asphalt in the vacuum tower is 1244.75 MJ, and the energy consumption in the propane deasphalting unit is 2318.37 MJ, of which CO_2 emissions are 28.69 kg and 13.62 kg respectively.

4.3. Estimation of Energy Conservation and Emissions Reduction of CRMAs

Compared to conventional asphalt, CRMAs consume less energy and produce less emissions because they use less asphalt. The amount of energy that can be conserved by replacing a portion of asphalt with rubber powder is calculated using Equation (9):

$$E = E_A - E_{RA} \tag{9}$$

$$E_{RA} = E_A \times \frac{1}{1 + P_A} + E_R \times \frac{P_A}{1 + P_A} \tag{10}$$

where E denotes the amount of energy conserved; E_A is the amount of energy consumed during asphalt production; E_{RA} is the amount of energy consumed during CRMA production; and P_A represents the amount of rubber mixed into the CRMA; E_R is the amount of energy consumed during the production rubber powder.

The savings in terms of energy conserved, emissions reduced, and costs decreased because of mixing rubber powder in the matrix asphalt are shown in Table 9.

Table 9. Effects of partial replacement of asphalt with waste rubber powder.

Substance	Energy Consumption (MJ/t)	CO_2 (kg/t)	Purchase Cost (USD)
Asphalt	3563.12	42.31	380.09
CRMA	3326.17	34.68	351.09
Savings (Asphalt-CRMA)	236.95	7.63	29.00

The energy consumption for producing 1 metric ton of asphalt is 3563.12 MJ, 42.31 kg of carbon dioxide in the process meantime. The energy consumption of one metric ton of waste rubber powder produced by dry process is 1071.43 MJ. Adding 22% of the waste rubber powder to the asphalt,

which significantly reduces the amount of asphalt material, saves energy consumption by 236.95 MJ, and reduces carbon dioxide emissions by 7.63 kg.

5. Estimation of Energy Conservation and Emissions Reduction of Warm-Mix CRMAs

The production of hot-mix asphalt mixtures requires heating of the asphalt and mineral materials to high temperatures, which consumes a substantial amount of energy. Furthermore, this process releases large quantities of harmful gases, and dust during production and construction, which can severely affect the quality of the surrounding environment and the physical health of construction personnel. Therefore, substituting warm-mix asphalt mixtures for hot-mix asphalt mixtures will no doubt offer substantial environmental and social benefits.

5.1. Estimation of Energy Conservation of Warm-Mix CRMAs

5.1.1. Parameter Determination

The commonly used viscosity temperature curve for determining the compaction temperature is not applicable for CRMA due to its high viscosity. This study used SGC methods to make various warm-mix CRMA mixtures specimens at five different temperatures (130 °C, 140 °C, 150 °C, 160 °C, 170 °C), four identical specimens were made for each set. The average porosity is shown in the figure. The compaction temperature of the warm-mix CRMA mixtures is determined by the porosity. The relationships between specimen porosity and compaction temperature are shown in Figure 3.

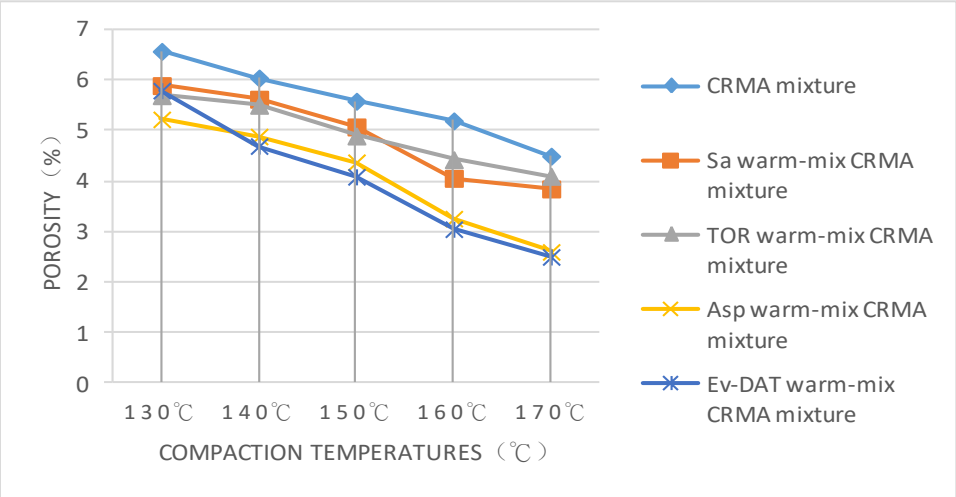


Figure 3. Relationship between porosity and compaction temperature.

Based on the objective porosity of 4.5%, the optimal compaction temperatures of the various warm-mix CRMA mixtures were determined and the optimal mixing temperature is determined following the principle that the mixing temperature should be 10 °C~15 °C higher than the compaction temperature. The optimal compaction temperatures of the hot-mix CRMA mixture, the Sa warm-mix CRMA mixture, the TOR warm-mix CRMA mixture, the Asp warm-mix CRMA mixture, and the Ev-DAT warm-mix CRMA mixture were 170 °C, 154 °C, 157 °C, 146 °C, and 144 °C, respectively. The temperature requirements of various construction processes are shown in Table 10.

Considering the way that concrete plants set up tents to cover aggregates, the pre-heating temperature of aggregates (including their moisture content) was set at 25 °C in the calculations. The specific heat capacity of liquid asphalt, aggregate, and water was 1340 $J\cdot(\text{kg }^{\circ}\text{C})^{-1}$, 920 $J\cdot(\text{kg }^{\circ}\text{C})^{-1}$, and 4190 $J\cdot(\text{kg }^{\circ}\text{C})^{-1}$, respectively. The latent of water under atmospheric pressure (0.1 MPa) is 2257.6 kJ/kg. Free water content was set at 4%. The warm-mix agent Aspha-Min contains 21% of crystal water that will be released when they encounter heat during mixing. Considering the heat loss

caused by water evaporation and steam dissipation, energy consumption was calculated based on that the water is completely evaporated at 120 °C. Heavy oil with combustion heat of 39.36×10^6 J·kg^{-1}, combustion efficiency of 90%, and a rate of heat exchange with heating roller of 60% served as the fuel of the asphalt mixing plant.

Table 10. Temperature requirements of various construction processes for different asphalt mixtures.

Temperatures of Construction Processes	Asphalt Discharge Temperature (°C)	Aggregate Discharge Temperature (°C)	Mixing Temperature (°C)	Compaction Temperature (°C)
CRMA mixture	185	190	180	170
Sa warm-mix CRMA mixture	185	165	164	154
TOR warm-mix CRMA mixture	185	170	167	157
Asp warm-mix CRMA mixture	180	170	156	146
Ev-DAT warm-mix CRMA mixture	180	145	154	144

5.1.2. Estimation Results

Based on energy consumption Equations (1)–(6), the amounts of energy and heavy oil consumed by the production of the five CRMA mixtures were calculated and the results are shown in Table 11. It consumes 300.89 MJ for producing one metric ton of hot mix asphalt mixture. The warm mixing can reduce energy consumption by 18~36%. The production of Ev-DAT warm-mix CRMA consumed the least amount of energy, conserving approximately 36% and thereby saving 2.76 kg of heavy oil compared to hot mixing. The next most energy-saving CRMA was the Sa warm-mix CRMA, which reduces energy consumption by approximately 20%, while Asp warm-mix CRMA and TOR warm-mix CRMA conserve about 18%. Thus, the amount of energy conserved by Ev-DAT warm-mix CRMA is roughly twice that of Asp warm-mix CRMA and TOR warm-mix CRMA.

Table 11. Energy and heavy oil consumption of different mix CRMAs.

Asphalt Mixture		Total Energy Consumption (MJ)	Energy Conserved (%)	Heavy Oil Consumption (kg)	Heavy Oil Conserved (kg)
Hot mixing	CRMA	300.89	—	7.65	—
Warm mixing	Sa-CRMA	238.62	20.69	6.07	1.58
	Ev-DAT CRMA	192.33	36.08	4.89	2.76
	TOR-CRMA	245.83	18.30	6.25	1.40
	Asp-CRMA	245.87	18.28	6.25	1.40

5.2. Estimation of Emissions Reduction of Warm-Mix CRMAs

5.2.1. List of Gases Released during Mixing

List of Gases Released during Fuel Combustion

Based on the amount of heavy oil consumed and the emissions coefficient of heavy oil combustion, the emissions generated by fuel consumption can be obtained. Using Equation (11), the amount of harmful gas emissions produced by the different CRMA mixtures was calculated. Table 12 lists the gases produced by heavy oil combustion.

$$E_{i,j} = M_j \eta_i \tag{11}$$

where $E_{i,j}$ is the amount of gas i released by the heavy oil combustion process during the production of CRMA mixture j; M_j indicates the amount of heavy oil consumed by CRMA mixture j; and η_i is the heavy oil combustion emissions coefficient of gas i.

Table 12. List of gases released by heavy oil combustion.

CO_2 (g)	CH_4 (g)	N_2O (g)	SO_2 (g)	CO (g)	NO_X (g)
2990.64	0.12	0.02	70.01	41.94	2.57

Equation (12) is used for calculating the emissions reduction effects of different warm-mix CRMA mixtures, the results of which are presented in Table 13.

$$E_j = E_H - E_{W,j} \tag{12}$$

where E_j represents the emissions reduction achieved by warm-mix CRMA mixture j; E_H is the amount of emissions produced by combustion during hot mixing; and $E_{W,j}$ denotes the amount of emissions produced by combustion during warm-mix CRMA mixture j.

Table 13. Emissions reductions of different warm-mix CRMA mixtures.

Emissions Reduction Effect	CO_2 (g)	CH_4 (g)	N_2O (g)	SO_2 (g)	CO (g)	NO_X (g)
Sa warm-mix CRMA mixture	4814.93	0.19	0.04	112.70	67.52	4.14
Ev-DAT warm-mix CRMA mixture	8313.98	0.33	0.07	194.60	116.59	7.14
TOR warm-mix CRMA mixture	4276.62	0.17	0.04	100.10	59.97	3.68
Asp warm-mix CRMA mixture	4336.43	0.17	0.04	101.50	60.81	3.73

The emission of fuel combustion depends exclusively on the amount of fuel consumed. Therefore, the Ev-DAT warm-mix CRMA mixture, which uses the least fuel, achieves the greatest effect, followed by the Sa warm-mix CRMA mixture, the Asp warm-mix CRMA mixture, and the TOR warm-mix CRMA mixture.

List of Gases Released during Heating

The gases released during the mixing process include the gases produced by asphalt oxidation and rubber aging. The underlying principle of CRMA production is the rubber powder added to asphalt followed by thorough mixing at high temperatures. When the rubber powder absorbs the light oil in the asphalt, a physical swelling reaction occurs, as shown in Figure 4. During this process, the reactions between rubber powder and asphalt are purely physical and release no new gases. At high temperatures, asphalt oxidizes rapidly and asphalt contains a variety of hydrocarbons whose functional groups produce CO_2 during oxidation processes. Rubber powder is made from waste rubber tires via physical methods, so rubber powder has the same composition as waste rubber tires. Heat accelerates the aging process of rubber, producing harmful gases such as CO, SO_2, H_2S, and NO_2. The aging process of rubber and its gas products are displayed in Figure 5. The real mixing process is simulated in the laboratory. Small scale asphalt heating and mixing laboratory simulator was adopted, and raw materials were added to the mixing tank of the simulator. The mixing tank has a temperature sensor and a heating module which can display and adjust the mixing temperature respectively. This simulator provides accurate data and is used for small amount of mixtures production. A gas detector was used to measure the gas concentration and detect harmful gases inside the mixing tank after the completion of mixing. The results of this simulation are presented in Table 14.

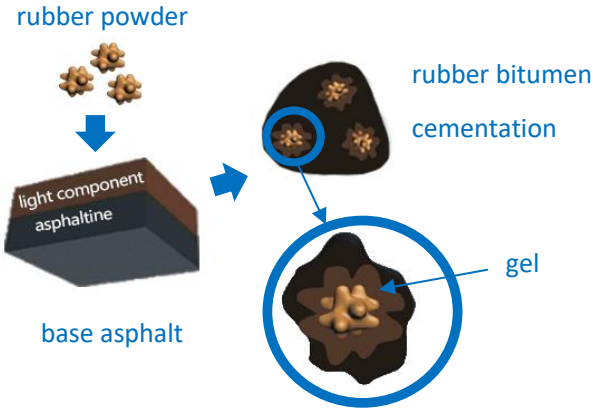


Figure 4. Swelling reaction of CRMA.

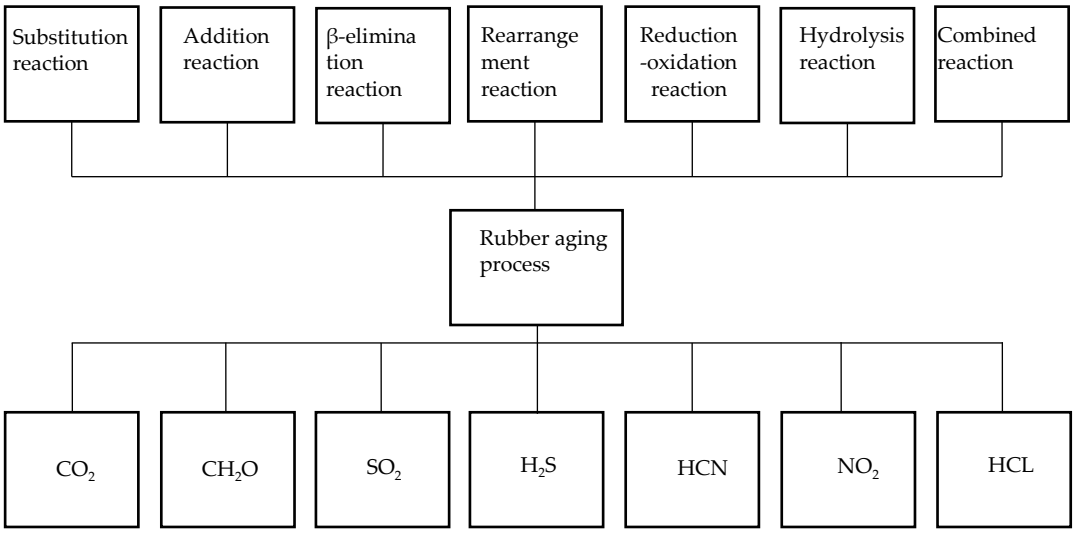


Figure 5. Process and gas products of rubber aging.

Table 14. List of harmful gases released during mixing.

Gas Emissions	Hot Mixing	Warm Mixing			
	CRMA	Sa-CRMA Mixture	Ev-DAT-CRMA Mixture	TOR-CRMA Mixture	Asp-CRMA Mixture
CO_2 (mg/m^3)	65.8 × 10^3	45.4 × 10^3	24.8 × 10^3	51.7 × 10^3	28.1 × 10^3
CO (mg/m^3)	106.3	76.3	47.3	78.1	53.4
NO_X (mg/m^3)	147.6	86.7	51.2	87.5	56.1
SO_2 (mg/m^3)	26.2	12.3	8.3	14.2	8.9
Dust (mg/m^3)	70.1	39.7	13.8	40.6	27.1

The emissions reduction achieved by the warm-mix CRMA mixtures are presented in Figure 6. As the results show, the use of warm mixing significantly reduces the amount of harmful gases released during the production process of CRMA mixtures, decreasing NO_x, SO_2 and dust emissions by more than 40%. The Ev-DAT warm-mix CRMA mixture presented the best effects, followed by the Asp warm-mix CRMA mixture, the Sa warm-mix CRMA mixture, and the TOR warm-mix CRMA mixture. The Ev-DAT warm-mix CRMA mixture was particularly effective in reducing CO and CO_2 emissions, approximately 2–3 times more effective than the TOR warm-mix CRMA mixture.

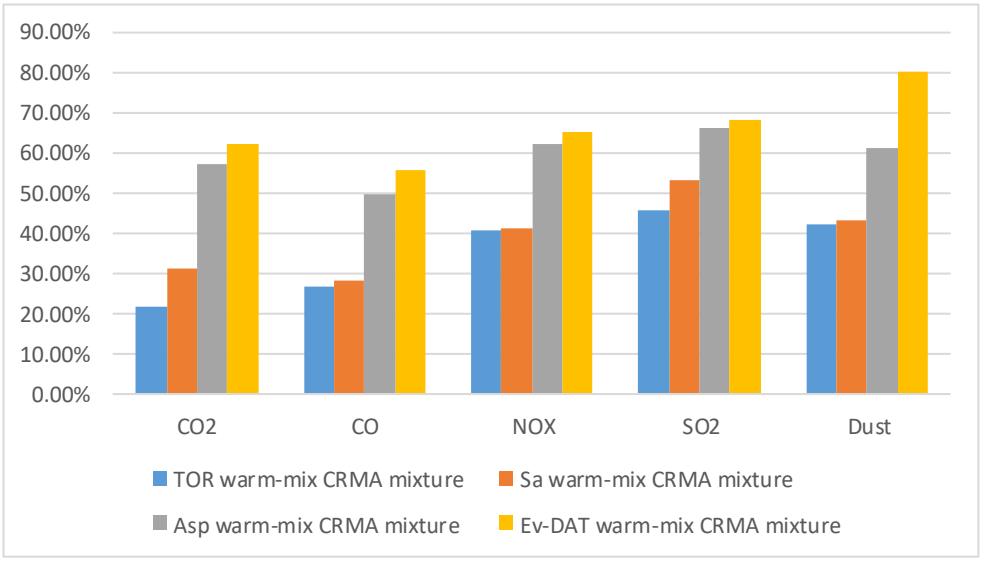


Figure 6. Emissions reductions achieved by different warm-mix CRMA mixtures during mixing.

5.2.2. List of Gases Released during Paving

At a construction site, the amount of harmful gases, including asphalt fumes, benzene soluble matter, and benzopyrene, produced during the paving of hot-mix and warm-mix CRMA mixtures was measured. The results are shown in Table 15 and Figure 7.

Table 15. List of gases released during paving.

Gas Emissions	Hot-Mix CRMA Mixture	Asp Warm-Mix CRMA	TOR Warm-Mix CRMA	Ev-DAT Warm-Mix CRMA	Sa Warm-Mix CRMA
Asphalt fumes(mg/m^3)	22.80	8.56	9.89	6.03	9.09
Benzene soluble matter (mg/m^3)	20.50	3.39	9.10	2.79	8.63
Benzopyrene ($\mu g/m^3$)	0.56	0.12	0.28	0.09	0.16

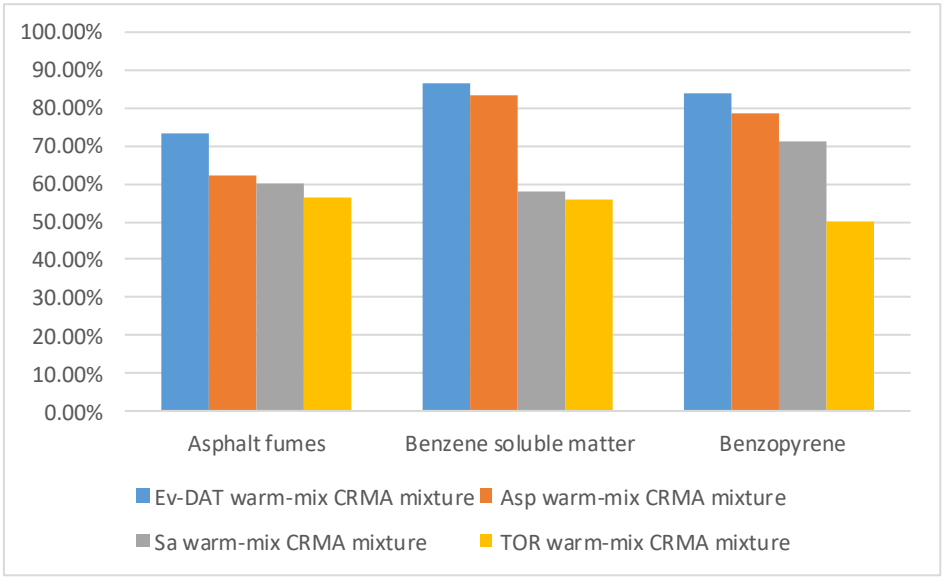


Figure 7. Emissions reduction achieved by different warm-mix CRMA mixtures during paving.

The results show that the use of warm mixing significantly reduces the amount of harmful gases released during paving. The Ev-DAT warm-mix CRMA mixture achieved the best effects (over 70%), followed by the Asp warm-mix CRMA mixture (over 60%). The Sa warm-mix CRMA mixture and the TOR warm-mix CRMA mixture reduced emissions by more than 50%. Thus, using warm mixing can substantially reduce the volatilization of asphalt fumes and greatly improve the work environment of construction workers.

5.3. Economic Benefits

A cost analysis of the four warm-mix CRMA mixtures was performed and the results were compared to the hot-mix CRMA mixture to determine the economic benefits of warm mixing. The prices of various warm-mix agents in China were investigated and the additional costs required for each metric ton of asphalt mixture based on the mixing amount of each type of warm-mix agent were calculated. The price of heavy oil was set at 584.75 USD/t. The amount of heavy oil needed to produce 1 metric ton of asphalt concrete and a cost analysis of warm mixing are as shown in Table 16.

Table 16. Cost analysis of warm mixing.

	Sasobit	**Ev-DAT**	**TOR**	**Aspha-Min**
Market price (USD/t)	5992.05	2776.80	16080.70	146.19
Mixing amount (kg/t)	1.50	0.40	0.50	2.50
Cost of warm-mix agent (USD/t)	8.99	1.11	8.04	0.37
Amount of heavy oil reduction (kg/t)	1.61	2.78	1.43	1.45
Changes in mixture cost (USD/t)	+8.11	−0.51	+7.20	−0.48

The cost analysis presented in Table 16 shows that for each metric ton of CRMA mixture produced, the Ev-DAT warm-mix CRMA mixture and Asp warm-mix CRMA mixture reduced costs by USD 0.51 and USD 0.48, respectively, whereas the TOR warm-mix CRMA mixture and Sa warm-mix CRMA mixture increased costs by USD 7.2 and USD 8.11. The production cost of hot-mix CRMA is generally 105 to 135 US dollars per metric ton. The use of different warm-mix agents can increase the cost by 7.7% maximum and reduce the cost by 0.5% maximum for every metric ton of CRMA.

All four warm-mix agents lower the mixing and paving temperature by 13 °C to 16 °C, which is close to the experimental results of the mixing temperature effect 20 °C stated in previous study [15]. Ev-DAT warm-mix CRMA has the best energy conservation and emission reduction effect among all four types of warm-mix agent. The application of warm-mix agent reduces the consumption of heavy oil and fuel by more than 18% and 13% respectively. The fuel saving reduces the fuel cost, while the use of warm-mix agent increases the cost. Ev-DAT warm-mix CRMA is the most cost-effective among all others by saving 0.5% of the cost per metric ton of mixtures.

6. Conclusions

This study established a model for the estimation of energy conservation and reduction in harmful emissions of waste rubber powder production, asphalt production, and the mixing and paving of warm-mix CRMAs. The energy consumption and emissions of waste rubber powder and asphalt production were estimated. A mixing amount of 22.00% of waste rubber powder can replace approximately 18.03% of the matrix asphalt in weight. The energy consumption required to produce 1 metric ton of CRMA mixture is reduced by 265 MJ, meanwhile the emissions of CO_2 is reduced by 3.76 kg and the cost is reduced by $29.00. The incorporation of waste rubber powder into asphalt has great benefits for energy conservation and environment protection.

CO_2 emissions of hot-mix CRMA mixture and four common warm-mix CRMA mixtures during mixing and paving were measured to serve as an estimation index for emissions reduction. Measurements of other harmful gases released during mixing were obtained in a laboratory simulation and expressed as content per unit volume. The harmful gas emissions of paving were measured

at the construction site. Based on these experimental data, the gas emissions comparison lists were established for the five CRMA mixtures during mixing and paving.

In this study, the utilization of warm-mix agents lowers the mixing temperature by 13 °C~26 °C, which saves fuel consumption and significantly reduces gas emissions. The four warm-mix CRMA mixtures consume less energy and produce lower gas emissions than the hot-mix CRMA mixture. To produce every metric ton of CRMA mixture, warm mixing can reduce energy consumption by 18~36% compared to hot mixing. All four warm-mix agents greatly reduced the amount of gases released by 15~87%, and the generation of asphalt fumes by 56.6~73.6% during different stages. Among the four types of warm-mix CRMA mixtures, the Ev-DAT warm-mix CRMA mixture conserved the most amount of energy and produced the least emissions. Additionally, the Ev-DAT warm-mix CRMA mixture was also the cheapest, which reduce the costs by USD 0.51 per metric ton of asphalt mixture. Due to the technique limitation, this study lacks the measurement of the total gas emission from the mixing and paving process. Therefore, the absolute value of the emission reduction cannot be derived. Additionally, the different type of warm-mix agents has little effect on the energy consumption and gas emission during transportation and paving. It is only affected by the transportation distance and paving equipment. This study does not conduct in-depth research for the transportation and paving stages. The entire life cycle of CRMA will be studied in future researches.

The application of warm-mix CRMA can effectively save energy and reduce harmful gases emission. It can also achieve more efficient use of rubber resource, save non-renewable resources, such as heavy oil by 18%, reduce pollution, and increase environmental sustainability. The warm-mix CRMA is a highly efficient pavement material that can conserve nonrenewable resources and reduce emission.

Since the energy consumption of different CRMA is the same in the transportation and paving process, this study does not measure the energy consumption of these two stages. Future study will cover the entire CRMA production process and through thermogravimetric analysis and differential scanning calorimeter to get more comprehensive data. Based on the results of this study, the proposed emission estimation model can be applied to establish the technical standard and assess the energy conservation of warm-mix CRMAs.

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