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Research Article

A Comparative Life Cycle Assessment (LCA) of Warm Mix Asphalt (WMA) and Hot Mix Asphalt (HMA) Pavement: A Case Study in China

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Generally, the warm mix asphalt (WMA) technology can reduce the mixing and paving temperature effectively as compared with that of hot mix asphalt (HMA), which is considered more environment-friendly. In this study, the environmental impacts and resource consumptions of WMA and HMA pavements were analyzed comparatively using the life cycle assessment (LCA) method. A LCA model of pavement was built; meanwhile, the relevant life cycle inventory (LCI) of WMA and HMA pavements was also collected and analyzed. The midpoint impact categories including Global Warming Potential (GWP), Chinese Abiotic Depletion Potential (CADP), and Particulate Matter Formation (PMF) were assessed for five cases. The assessment results showed that the resource consumptions of both WMA and HMA pavements in entire life were almost at the same level, while the environmental impacts of WMA pavement related to greenhouse gases and $PM_{2.5}$ emissions were significantly less than that of HMA pavement, except for the case where the long-term performance of WMA pavement is much worse than that of HMA pavement. In final, it could be concluded that WMA pavement is more environment-friendly compared with HMA pavement although they have the same-level resource consumptions.

1. Introduction

Nowadays, transport is vital for the well-functioning of economic activities and a key to ensuring social well-being and cohesion of populations. Transport ensures everyday mobility of people and is crucial to the production and distribution of goods. Transport infrastructure refers to the framework that supports our transport system and is a fundamental precondition for transport systems. However, the construction and maintenance of transportation infrastructures has become and will continue to be a significant contributor to the consumption of raw materials and greenhouse gases emissions worldwide. In America, more than 350 million tons of raw materials were consumed each year in highway construction and maintenance [1]. A third of total CO_2 emissions were contributed by the transportation industry in Denmark, of which 95% comes from the construction and operations of transportation infrastructures [2]. In China, the highway industry contributed about 290 million tons of CO_2 emissions in 2004, and the predicted emission is expected to reach 1.1 billion tons in 2030 [3].

In recent years, the mileage of highway has been reached 108,000 kilometers in China. Asphalt pavement is the dominating pavement form in expressway due to the following advantages: smooth surface, comfortable driving, low noise, simple construction, and rapid open-to-traffic. Nevertheless, due to the high manufacturing temperature (150~190°C) of typical hot mix asphalt (HMA) mixtures, the energy consumptions (fuel oil and electricity usage, etc.) and gases emissions (CO_2 and other pollutants) are quite high during the construction process. In order to construct environment-friendly pavements, the warm mix asphalt (WMA) mixture, which has the relatively lower manufacturing temperature of 100~140°C and has similar mechanical properties to that of HMA mixture, has drawn much attention in the past decade [4–6].

WMA mixture has a lower viscosity and remains in good workability at a relatively lower temperature by adding viscosity-reducing agents (e.g., Sasobit and Evotherm) or incorporating water (e.g., Asphalt-min and Double Barrel Green) during the mixing process [7, 8]. Among them, chemical additives including a combination of emulsification agents, surfactants, polymers, and other additives were normally used to improve coating, mixture workability, compaction, and adhesion performances of asphalt. A series of studies have been conducted to compare the environmental impacts between HMA and WMA mixtures [9–11], which showed that WMA had the advantages of lower energy consumption, fewer emissions, and better working condition during mixing and paving process. However, the long-term performances of WMA pavement are not very clear, and water damage is easier to occur in WMA pavement than that in HMA pavement. Furthermore, the energy consumptions and environmental impacts of the upstream supply chains (e.g., the production of additive agents and transportation) and downstream processes (e.g., operation and maintenance) have not been considered in previous studies. Therefore, a more systematic and complete comparative assessment between WMA and HMA is necessary to be studied.

Life cycle assessment (LCA) is a useful method to assess the environmental impacts of a product system throughout its entire life cycle, including extracting and processing of raw materials, manufacturing, transportation, utilization, maintenance, recycling, and final disposal during end-of-life stage [12–15]. In the mid-1990s, Häkkinen first introduced the concept of LCA into pavement engineering by comparing the environmental impacts of portland cement concrete (PCC) and stone mastic asphalt (SMA) pavements in Finland [16]. They concluded that the CO_2 emission of PCC pavement is 40%~60% more than that of SMA pavement; however, the nonrenewable energy consumption of SMA pavement is twice more than that of PCC pavement due to the high feedstock energy of asphalt. Following their pioneering research, a series of studies associated with LCA on pavement engineering was conducted. For example, Yu built an LCA model to evaluate the environmental impacts of pavement, and concluded that the portland cement concrete (PCC) pavement had a smaller environmental burden as compared with that of HMA [17]. Horvath evaluated the environmental impacts of HMA and continuously reinforced concrete pavement (CRCP) pavements in America using economic input-output life cycle assessment model [18]. Nevertheless, most of the researchers (e.g., Wilfred [19], Berthiaume and Bouchard [20], Nisbet et al. [21], and Stripple [22]) just focused on the comparison between traditional HMA pavement and PCC pavement due to limited data availability for the other pavement forms. Due to the relatively new technique of WMA for pavement construction, to date, the LCA study of WMA pavement was still rarely conducted. Tatari et al. assessed the environmental impacts of different types of WMA pavement and constructed a comparison between the WMA pavement and the traditional HMA pavement based on a hybrid LCA model. The results demonstrated that it should not be the only phase to evaluate the amount of atmospheric emission of asphalt pavements, although the mixing phase is important [23]. Rosario et al. assessed the environmental impacts of HMA and zeolite-based WMA with reclaimed asphalt pavement (RAP) material. It concluded that during the entire life cycle, the impacts of zeolite-based WMA pavements were almost equal to the impacts of HMA pavements with the same RAP content [24].

In this study, it emphasizes on the comparative assessment associated with environmental impacts between WMA and HMA pavements using LCA method. Firstly, the LCA models of these two pavements were built and the research scope was identified, including the production of asphalt, aggregates and chemical additives, asphalt mixture manufacturing and transportation, pavement construction and operation, maintenance, and dismantling at the end of life. Furthermore, the inventory data including raw materials/energy consumptions and environmental emissions of WMA and HMA pavements in all stages were collected and analyzed. Finally, five cases were assumed for long-term performances of WMA pavement to comparatively analyze the environmental impacts for these two pavements.

2. LCA Method and Model of Pavement

2.1. Goal and Scope Definition. According to ISO standards [25, 26], generally, LCA incorporates four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation. The goal and scope definitions of LCA determine the guidelines to be followed during the rest of the assessment. The goal decides the model type and evaluation index of LCA. This study aimed to evaluate the environmental impacts and resource consumptions of WMA and HMA pavements during their entire life cycle, which is expected to facilitate more informed decision as environment-sensitive pavement construction comes with the uncertainty of newly constructed WMA pavement. Whenever possible, local data from Chinese practice will be adopted. In the situation of the unavailable data, complementary data from elsewhere, such as European Bitumen Association (EBA) and US Environmental Protection Agency (EPA), will be adopted to complete the study.

The scope of LCA has a direct impact on the collection of inventory data. Generally, the life cycle of road pavements included six major stages: pavement design, raw materials' production, transportation, construction, use, maintenance, and final disposal at the end of life [27]. The environmental impacts in the pavement design stage are mainly involving the print of blueprints and transportation of designers, which could be negligible compared with the other stages. Additionally, the environmental impacts in the use stage of pavement are mainly including the fossil fuel combustion of the vehicle, which is assumed to be the same for both WMA and HMA pavements. Therefore, the stages of pavement design and use were not included in this study. The main differences between environmental impacts and resource consumptions between WMA and HMA pavements are from asphalt mixture production, and this process will be analyzed separately. Based on the above descriptions, the scope of the pavement LCA model in this study consisted of the following stages: raw materials' production and transportation, asphalt mixture production and transportation, pavement construction and maintenance, and disposal at the end of life, as shown in Figure 1.

The life cycle of WMA and HMA pavements in this study started from the stage of raw materials' production. The raw materials mainly included aggregates (sand, mineral powder, and macadam), asphalt binders (petroleum asphalt and modified asphalt), and warm-mixing agents. The resource consumptions at this stage mainly include heavy oil, diesel oil, gasoline, and electricity, which are consumed by the operation of relative machines used to produce and process raw materials, while the environmental impacts mainly come from mineral extraction, asphalt refinement, production of warm-mixing agents, and transportation of these raw materials to the asphalt-mixing plant.

As the raw materials were transported to the asphalt-mixing plant, the aggregates will be dried and screened; meanwhile, the asphalt would be heated. Then, the asphalt mixture was produced and transported to the construction site of pavement. The main resource consumptions are fuel and electricity used by machinery in the processes of drying and screening, heating and mixing, and transportation. The environmental impacts in this stage are mainly caused by the burning of fossil fuels.

The stage of pavement construction comprises the following processes: site cleaning and preparation, foundation compaction, construction of subbase and base layers, asphalt-mixture paving, levelling, and rolling. As the difference of environmental impacts between WMA and HMA pavement construction lies in the process of asphalt-mixture paving, only this process was assessed in this stage. The main resource consumption is fossil fuel used by paving machinery. The gas emissions in this stage are mainly from the burning of fossil fuels and the hot/warm asphalt mixture.

After a certain period of service, the pavement needs to be maintained due to its deterioration with the combination of environmental impacts and repeatable vehicle loading. In this study, for simplification, it was assumed that only medium repair with overlay will be adopted. The environmental impacts in this stage are mainly involving the demolition of damaged asphalt layers, cleaning the substrate, and paving a new layer of asphalt mixture.

At the end of service life, the pavement materials need to be properly disposed of. There are a number of options for end-of-life treatment, such as abandonment (together with pavement), landfill, or recycling. In this study, the recycling option was selected due to its high popularity. The resource consumptions and pollution emissions are mainly from the burning of fossil fuel by the equipment during demolition, transport, and landfill.

2.2. Functional Unit. The functional unit was defined as a quantitative benchmark unit that should represent the function of the analyzed system. For a more accurate comparison, the same function unit for different road pavement systems is used in this paper. Herein, the function unit for road pavement LCA is defined based on the geometry, performances, and service life of the pavement. For the case study presented later, the section of road pavement with 6 lanes concerned has a length of 1 km and a width of 33 m. The entire service life of this road is assumed to be 15 years, which is the designed life of asphalt pavement. The average daily traffic volume is 20,000, of which 8% are heavy vehicles. The total thickness of the asphalt layer is 18 cm as the pavement structure consists of three layers from top to bottom, which is 4 cm stone mastic asphalt (SMA-13), 6 cm asphalt concrete (AC-20), and 8 cm AC-25, respectively, as shown in Figure 2. The compositions of asphalt mixture are listed in Table 1. Evotherm DAT manufactured by MeadWestvaco Co. Ltd. was used as the warm-mixing agent at dosage of 5% to asphalt by weight [28].

In the stage of asphalt-mixture production, the initial temperature of the raw materials is assumed as 25°C, and the mixing temperature of HMA and WMA mixtures is 180°C and 140°C, respectively. All asphalt mixtures are transported from the asphalt plant to the construction site with an assumed average distance of 10 km. In the stage of end of life, the demolished pavement materials were recycled.

The pavement condition index (PCI) deterioration model was used to determine the moment of maintenance conduction in this study [29]. The PCI can be calculated using

$$\mathrm{PCI} = \mathrm{PCI}_0\left\{1 - \exp\left[-\left(\frac{\alpha^{\beta}}{y}\right)\right]\right\}, \quad (1)$$

where PCI_0 is the initial pavement condition index, y is the age of road, and α and β are the service life index and geometric shape index, respectively.

In this study, the maintenance will be conducted when the PCI reduces to 70, after which the PCI will be upgraded to a level equivalent to that of before five years ago, as shown in Figure 3. The maintenance area is half of the total area specified in the functional unit.

For WMA pavement, there were five assumed maintenance scenarios to account for the uncertainty of its long-term performance: (1) the PCI of WMA pavement deteriorated slower than that of HMA pavement by 20%, and the maintenance area was 20% less than HMA; (2) the PCI of WMA pavement deteriorated 10% slower than that of HMA pavement, and the maintenance area was 10% less than HMA; (3) the WMA pavement has the same maintenance condition with HMA pavement; (4) the PCI of WMA pavement deteriorated 10% faster than that of HMA pavement, and the maintenance area was 10% larger than HMA pavement; and (5) the PCI of WMA pavement deteriorated 20% faster than that of HMA pavement, and the maintenance area was 20% larger than HMA pavement.

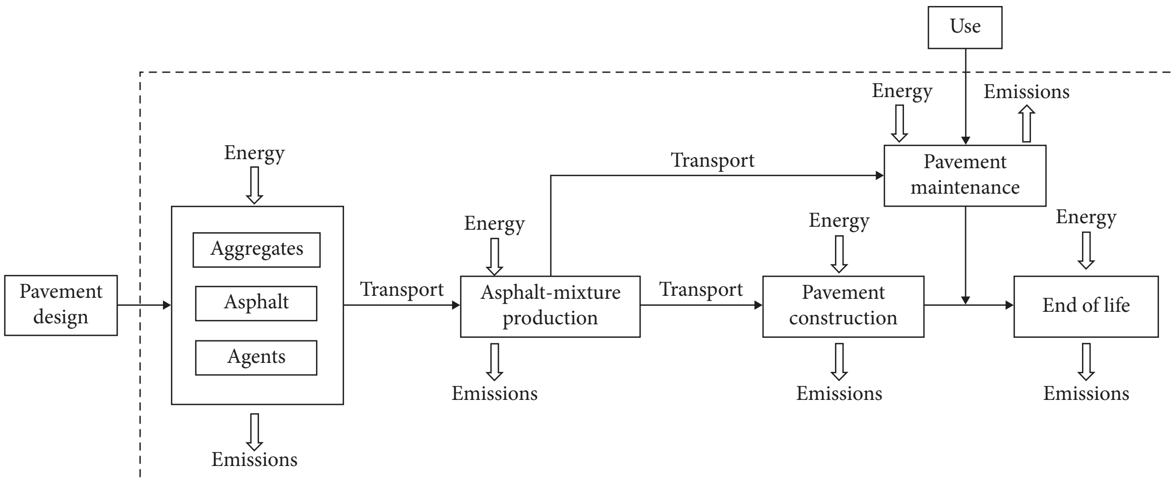

Figure 1: The scope of pavement LCA model in this study.

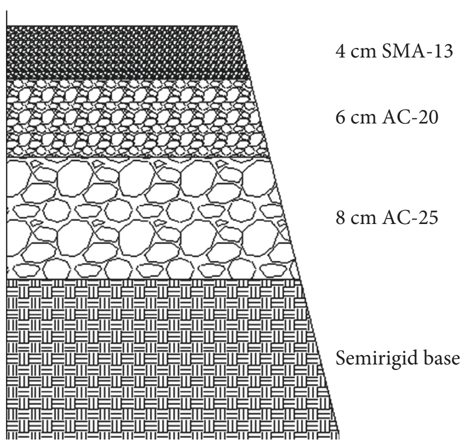

Figure 2: The pavement structure of asphalt pavement.

2.3. Life Cycle Inventory (LCI) Analysis

2.3.1. Raw Materials. The raw materials of asphalt mixture mainly include natural aggregates (sand, mineral powder, gravel, and stone chips), asphalt (petroleum asphalt and modified asphalt), and warm-mixing agents. The LCI of natural aggregates was from the Chinese Life Cycle Database (CLCD), which covers a large amount of LCI data for basic industry products in China, averaged over different scales of manufacturing and degree of technical sophistication. The LCI of asphalt comes from European Bitumen Association (EBA) because the CLCD lacks the environmental impact data for asphalt production, and the source of crude oil and refining process in China are the same as those in Europe. The Evotherm warm-mixing technology was used most widely in China for WMA mixture production, and hence, the LCI data were also from the Ecoinvent database from Europe.

2.3.2. Asphalt-Mixture Production. The energy consumptions during the production of asphalt mixture mainly involve fuel and electricity consumptions. The fuel is consumed for asphalt heating and aggregate drying, while the construction machinery consumes the electricity. During this process, the aggregates drying and heating are likely to bring out plenty of dust, while the burning of fossil fuel leads to CO_2 emission. Moreover, the asphalt heating during mixing releases a lot of harmful gases.

For the hot mixture asphalt (HMA), the energy consumptions are calculated using Chinese Highway Engineering Budget Quota and Machinery Quota (JTG/T B-06-02-2007) (JTG/T B-06-03-2007) (in short: Quota method). The number of machine team when producing every $1000\,m^3$ HMA was surveyed from the Budget Quota, whereas the energy consumptions of machinery in unit machine team were surveyed from Machinery Quota. Then, the energy consumptions can be calculated through the product of these two sets of data. The energy consumptions of producing $1000\,m^3$ coarse-graded asphalt (CGA) mixture are listed in Table 2. The pollutant emissions during the production of HMA were calculated based on the emission factors, including CO, CO_2, NO_X, SO_2, and $PM_{2.5}$ emissions, from the US Environmental Protection Agency (EPA) [30]. There are 0.2 kg CO emission, 18.5 kg CO_2 emission, 0.06 kg NO_X emission, 0.044 kg SO_2 emission, and 2.25 kg $PM_{2.5}$ emission, during the production of every one ton of HMA mixture. Based on the above descriptions, the LCI of mixing every $1000\,m^3$ HMA is calculated and listed in Table 3.

For warm mix asphalt mixture, the energy consumptions were calculated using the thermodynamic equilibrium:

$$M \cdot q \cdot \lambda \cdot \eta = \sum_i c_i m_i \cdot (T_f - T_i) + c_w m_w \cdot (T_w - T_i) + L_w m_w, \tag{2}$$

where M is the weight of fuel (kg), q is the calorific value of fuel (J/kg), λ is combustion efficiency, η is the heat exchange rate of equipment, n is the total number of aggregate type, c_i is the specific heat capacity of the i-th aggregate (J·kg^{-1}°C), m_i is the weight of i-th aggregate (kg), T_f the final temperature of aggregate after heating (°C), T_i is the initial temperature of aggregate (°C), c_w is the specific heat capacity of water (4190 J·kg^{-1}°C), m_w is the weight of water (kg), T_w is the boiling point of water, 100°C, and L_w is the latent heat of vaporization (2256 kJ/kg).

Table 1: Composition of 1000 m^3 asphalt mixtures.

Asphalt mixture	SBS-modified bitumen (t)	#70 asphalt (t)	Fiber stabilizer (t)	Sand (m^3)	Mineral powder (m^3)	Stone chip (m^3)	Gravel (m^3)
SMA-13	144.32	—	7.34	119.38	246.74	126.56	1111.35
AC-20	—	122.54	—	471.22	128.40	261.18	723.22
AC-25	—	113.47	—	389.79	117.72	226.75	854.79

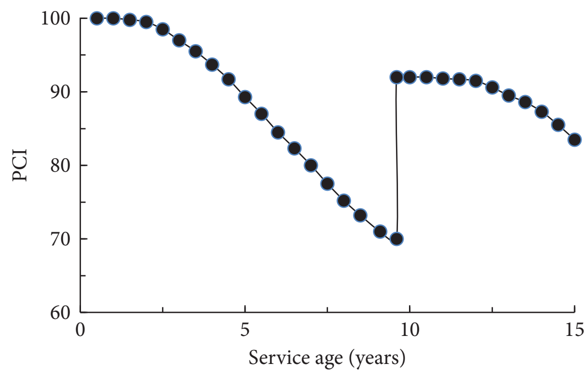

Figure 3: The change of PCI with age (maintenance event occurs at 10 years).

Table 2: Energy consumptions of producing 1000 m^3 coarse-graded asphalt (CGA) mixture.

Equipment	Machine team	Energy consumption per machine team			Total energy consumption		
		Heavy oil (kg)	Electricity (kWh)	Diesel oil (kg)	Heavy oil (kg)	Electricity (kWh)	Diesel oil (kg)
Mixer (320 t/h)	1.35	9574.4	5917.61	—	12925.44	7988.77	—
Loader (3 m^3)	2.53	—	—	115.15	—	—	291.33

Table 3: The LCIs of mixing every 1000 m^3 HMA and WMA mixtures.

Type of consumption/emission	Amount	
	HMA	WMA
Heavy fuel oil (kg)	12955.44	9900.55
Electricity (kWh)	7988.77	6105.02
Diesel (kg)	291.33	222.63
CO_2 (kg)	45510	18204
NO_X (kg)	147.6	40.44
SO_2 (kg)	108.24	26.84
$PM_{2.5}$ (kg)	10.33	5.38

As listed in Table 3, the calculation results indicate that the total resource consumptions during the production of WMA are 23.6% less than that of HMA. Qing et al. measured the actual resource consumptions during HMA and WMA mixing in asphalt-mixing plant [31]. Their results indicate that the energy consumption of WMA mixing is 22.1% less than that of HMA. Therefore, the thermodynamic equilibrium equation can be used reliably to predict the energy consumptions during the production of WMA in this study. Furthermore, their results indicate that compared with HMA, WMA emissions reduce significantly by 60%, 72.6%, 75.2%, and 47.9%, respectively, for CO_2, NO_X, SO_2, and $PM_{2.5}$. The LCI of mixing 1000 m^3 WMA is also listed in Table 3.

2.3.3. Transportation. The mixed asphalt mixture is transported by dumper truck from the asphalt-mixing plant to the construction site and poured into paving machinery. In this study, the carrying capacity of a dumper truck is assumed as 15 tons. The environmental impacts in this stage are from the burning of fuel by the vehicles. The energy consumptions also can be calculated using the Chinese Quotas mentioned before. 542.44 kg of diesel oil will be consumed when transporting 1000 m^3 asphalt mixture for 1 km distance. The gaseous emissions are calculated based on the emission factors, including CO_2, NO_X, CO, $PM_{2.5}$, N_2O, and NH_3, from the European Environment Agency (EEA) [32]. It produces 3140 g CO_2 emission, 33.4 g NO_X, emission, 7.58 g CO emission, 0.94 g $PM_{2.5}$ emission, 0.051 g N_2O emission, and 0.013 NH_3 emission as every 1 kg diesel oil was burnt during the running of equipment.

2.3.4. Construction. During the pavement construction stage, it comprises different processes, whereas this study just focused on the asphalt-mixture paving process. The energy consumptions in this stage come from the fuel consumed by the paver and roller compaction machinery, which are calculated through the Quota method. The diesel oil consumptions of constructing 100 m^2 stone mastic asphalt (SMA), medium-sized particle asphalt (MSPA), and coarse-graded asphalt (CGA) concrete pavement are 445.75 kg, 280.02 kg, and 279.71 kg, respectively. The gaseous emissions data are referenced from GB 20891-2007 and listed in Table 4.

Table 4: Gaseous emissions of constructing 100 m^2 asphalt concrete pavement.

Pavement type	Gases emissions				
	CO_2 (kg)	NO_X (g)	CO (g)	PM (g)	HC (g)
SMA	2817.11	89.25	60.95	3.57	14.87
MSPA	1793.62	70.62	47.29	2.76	11.68
CGA	1779.43	69.47	46.89	2.74	11.58

Table 5: The energy consumptions and pollution emissions of 1000 m^2 overlay.

Energy consumptions (kg)		Pollution emissions (kg)	
Heavy oil	583.44	CO_2	2340.63
Electricity	393.94	SO_2	4.73
Diesel oil	144.09	NO_X	13.41
Gasoline	1.03	CO	26.44
—	—	PM	257.57

2.3.5. Maintenance. The maintenance was conducted periodically throughout the entire service life of the pavement. In this study, only the overlay technology was chosen to maintain the distressed pavement. The energy consumptions were calculated using the Quota method. Due to the similarity of the necessary processes for both new construction and maintenance (only asphalt-mixture paving process considered in new construction, whereas the rest is considered the same for both HMA and WMA pavements), the pollution emissions of maintenance can be calculated similarly (Refer to Section 2.3.2 to 2.3.4). The energy consumptions and pollution emissions of 1000 m^2 overlay with 4 cm thickness are listed in Table 5.

2.3.6. End of Life. As mentioned previously, the environmental impacts were mainly from the use of fuel by demolition, transport, and landfill equipment at the end-of-life stage. The energy consumptions and pollution emissions can be calculated using the Quota method and emission factors from the European Environment Agency (EEA), respectively.

2.4. Impact Assessment and Sensitivity/Uncertainty Analysis

2.4.1. Impact Assessment. The impact assessments of WMA and HMA pavements were conducted using LCA-based software. These impacts were assessed in accordance with two sets of impact categories, which are midpoint impact categories and endpoint impact categories, respectively. The endpoint impact categories include damage to human health, damage to ecosystem diversity, and damage to resource availability. They may be affected by environmental conditions in different regions, such as atmosphere, water, soil, and ecological system. Due to a lack of such data in China, the endpoint impact categories were not assessed in this study.

Three midpoint impact categories, which are Global Warming Potential (GWP), Chinese Abiotic Depletion Potential-fossil fuel (CADP), and Particulate Matter Formation (PMF), were selected in this study to assess environment impacts and resource consumptions. GWP contains the impact factors of CO_2, CH_4, CO, and N_2O, which are characterized as CO_2 and expressed as GWP/kg. CADP is an exclusive midpoint impact category in China, which was obtained based on Abiotic Depletion Potential (ADP) of China applying CML method. The impact factors of CADP include coal, petroleum, and natural gas, of which the characteristic factor of CADP is coal, and expressed as CADP/kg. The impact factors of PMF contains of PM_{10} and $PM_{2.5}$. The characteristic factor is $PM_{2.5}$, which is expressed as PMF/kg.

2.4.2. Sensitivity and Uncertainty Analyses. The sensitivity analysis is used to quantitatively analyze the influence of inputs on the outputs for a mathematical model, which can be calculated using equation (3). Based on the analysis of sensitivity, the most effective improvements to reduce the environmental impacts can be obtained, i.e., identifying the most sensitive inputs for any particular output (an indicator of interest):

$$S_m = \frac{(\Delta O_m/O_m)}{(\Delta I_n/I_n)}, \tag{3}$$

where S_m is sensitivity, O_m is the first m result index value of LCA, and I_n is the first n LCI data.

The credibility of LCA results is influenced by uncertainty during the LCA processes. The uncertainty of LCA consists of original data uncertainty and algorithm uncertainty. The original data uncertainty can be assessed in terms of data source reliability, sample integrity, technical, time, and geographical representativeness. In this study, original data uncertainty was obtained from the Ecoinvent database [33] and calculated using the following equation:

$$U_r = \sqrt{\sum_1^5 U_i}, \tag{4}$$

where U_r is the original data uncertainty and U_i is the original data uncertainty in the first term.

The algorithm uncertainty depends on the rationality of the algorithm. The uncertainties of algorithms: directly acquire algorithm, total algorithm, balancing algorithm, experience algorithm, and theory algorithm are 0, 0, 0.025, 0.05, and 0.1, respectively [34]. Based on the above descriptions, the uncertainty of LCA results can be calculated using the following equation:

$$U = \sqrt{U_r^2 + U_a^2}, \tag{5}$$

where U is the overall uncertainty of LCA results, U_r is the original data uncertainty, and U_a is the algorithm uncertainty.

2.5. LCA-Based Tool. A commercial LCA-based software was used in this study to calculate the environmental impacts and resource consumptions of the WMA and HMA

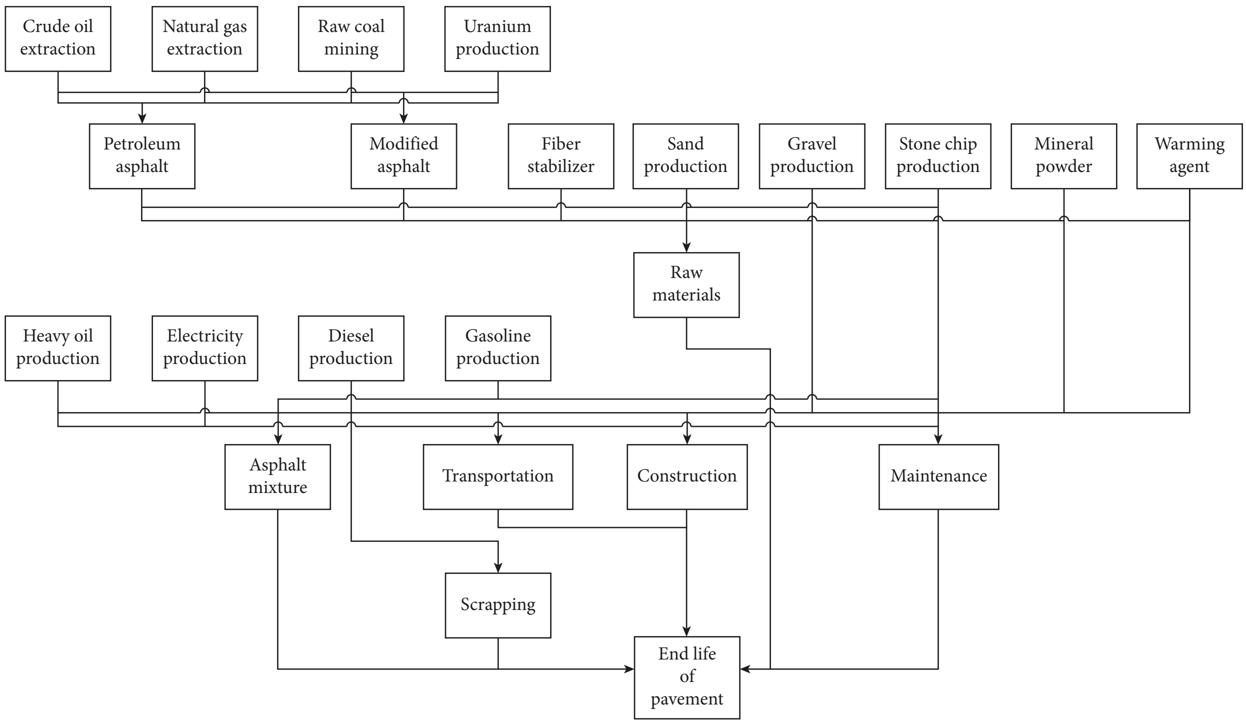

Figure 4: The LCA modeling process of WMA and HMA pavements in LCA-based software.

pavements. This software contains the key features of international popular LCA-based software, including data collection records and automatic generation of LCA reports. The inventory data can be obtained from Chinese life cycle database (CLCD), European life cycle database (ELCD), and Ecoinvent database, which are incorporated within this software. It also allows users to add new data and calculations to the database. The LCA modeling process of WMA and HMA pavements using this software is shown in Figure 4. In addition, the Microsoft Excel spreadsheet was also used to prepare the LCI data and helps the process of calculating environmental impacts of both pavements.

3. Assessment Results and Discussion

3.1. Impact Assessment

3.1.1. Impact Category of GWP. Figure 5 presents the GWP of HMA and WMA pavements for five cases. As can be seen, besides the case 5, which assumed WMA performance is much worse than HMA, WMA pavement exhibits pronounced reduction of total GWP when compared with HMA pavement. This is mainly caused by less fuel burning and CO_2 emission due to the lower mixing temperature of WMA, as indicated by a 46.7% GWP reduction of WMA over HMA when asphalt-mixture production is considered separately. On the other hand, the GWP of WMA pavement for raw materials' production is only 2.8% more than that of HMA pavement due to the addition of the warm-mixing agent. In case 5, although the long-term performance of WMA pavement is much inferior to that of HMA pavement, the GWP of WMA pavement is still comparable to that of HMA pavement. For case 5, the evident increase of GWP impacts in WMA pavement is attributed to the increased GWP value at the maintenance stage, of which the GWP value of WMA pavement is 2.13 times higher than that of HMA pavement due to the relatively higher maintenance times and area of WMA pavement as compared with HMA pavement.

3.1.2. Impact Category of CADP. Figure 6 shows the CADP of HMA and WMA pavements. As can be seen from Figure 6, the stage of raw materials' production has the highest contribution to the CADP in the entire life cycle. Although, in the cases 1 to 3, the CADP of WMA pavement is above 20% less than HMA pavement in the stages of asphalt-mixture production and maintenance, the adoption of warm-mixing agent in WMA pavement increases the CADP in the stage of asphalt-mixture production. Therefore, the total resource consumption of WMA pavement is slightly less than HMA pavement. However, in case 5, the CADP of WMA pavements is 14.3% more than that of HMA pavements because maintenances were conducted twice in the entire life cycle of WMA pavement.

3.1.3. Impact Category of PMF. Figure 7 illustrates the PMF of WMA and HMA pavements. As can be seen from Figure 7, although the PMF of WMA pavement for raw materials is slightly higher than that of HMA pavement due to warm-mixing agent production, WMA pavement has an obvious lower PMF compared with HMA pavement in cases 1 to 4. The reduction (about 47.4%) of PMF of the WMA pavement is mainly contributed from the stages of asphalt-mixture production due to the lower mixing temperature. The $PM_{2.5}$ emission reduces evidently with the lower mixing temperature. In case 5, there is no obvious difference of the PMF between WMA and HMA pavements

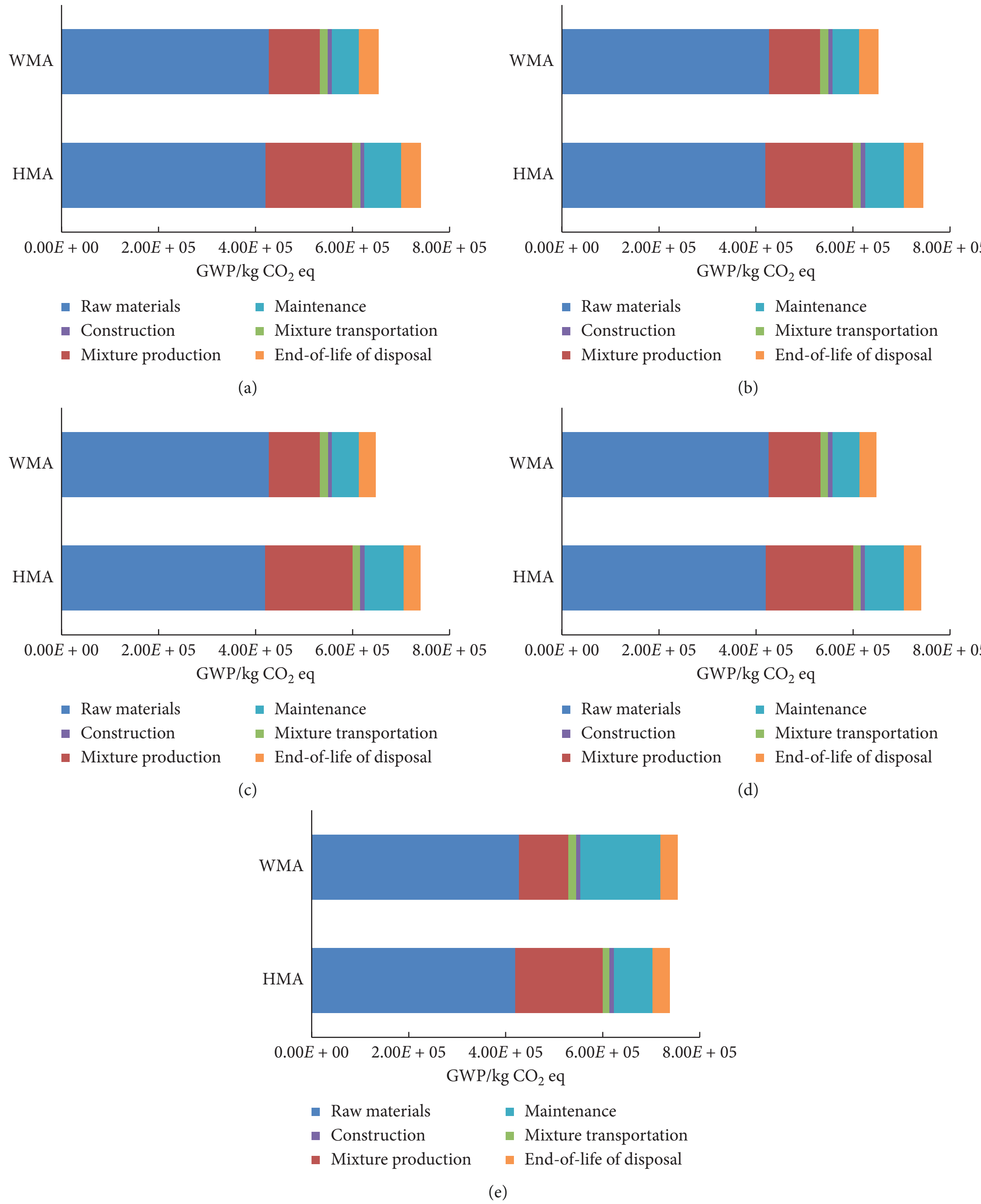

Figure 5: The GWP impacts of HMA and WMA pavements for five cases: (a) case 1; (b) case 2; (c) case 3; (d) case 4; and (e) case 5.

because maintenances were conducted twice on WMA pavement during the entire life cycle.

Based on the above discussions, constructing WMA pavement has almost no advantage of saving resources. Nevertheless, the WMA pavement has an obvious effect to reduce the greenhouse gases and $PM_{2.5}$ emissions. Therefore, popularizing WMA pavement is beneficial to the construction of environment-friendly society.

3.2. Results Assessments

3.2.1. Sensitivity Assessments. In this section, the sensitivity of impact category factors GWP, CADP, and PMF (relative change of factor induced by the change of unit process/inventory) was calculated. The pairs of unit process/factor that have sensitivity value larger than 10% are listed in Table 6. As can be seen from Table 6, the production of raw materials

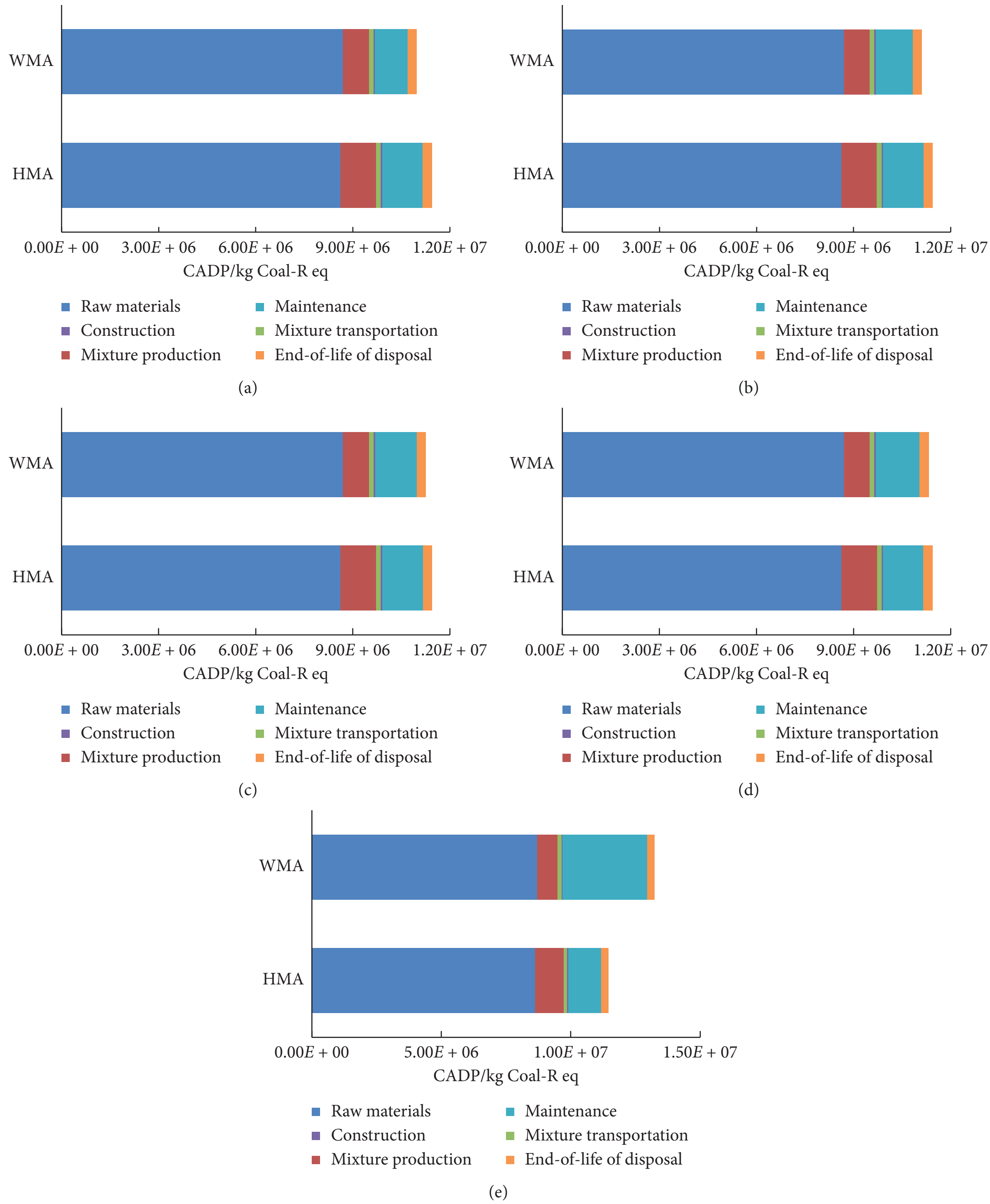

Figure 6: The CADP impacts of HMA and WMA pavements for five cases: (a) case 1; (b) case 2; (c) case 3; (d) case 4; and (e) case 5.

including petroleum asphalt and raw petroleum has the highest sensitivity for indexes GWP, CADP, and PMF. It suggests that improving the technology of raw materials' production, especially raw petroleum and asphalt production, is the most effective way to decrease the impact on the environment and the reduction of resource consumption. For WMA pavement, these unit processes and inventories have higher sensitivity as compared with HMA pavement, except asphalt-mixture production. It indicates that improving the technology of these unit processes, such as asphalt production and petroleum extraction, can be more effective to reduce GWP, CADP, and PMF for WMA pavement.

3.2.2. Uncertainty Assessments. In this study, an uncertainty assessment was also conducted to determine the

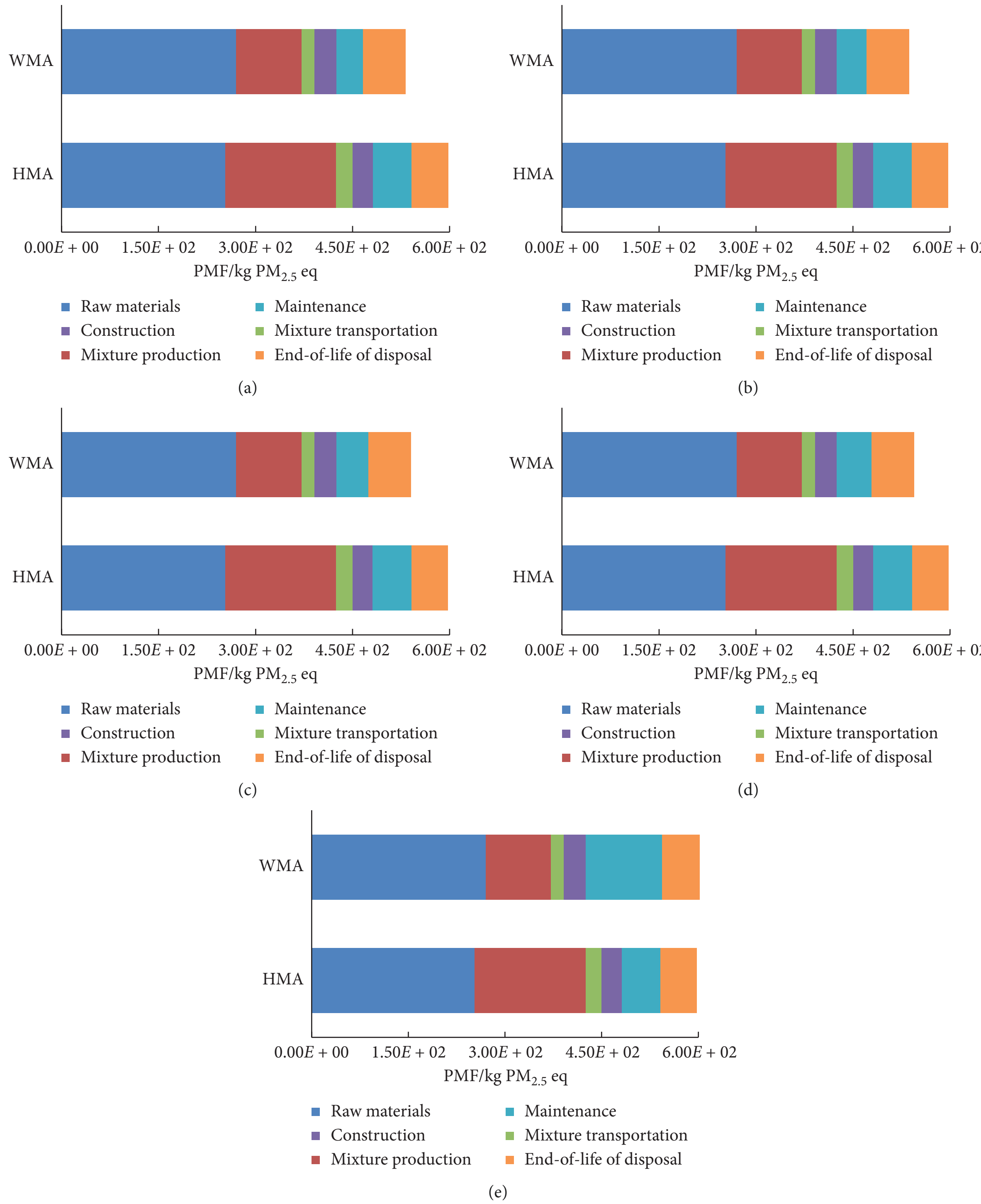

FIGURE 7: The PMF impacts of HMA and WMA pavements for five cases: (a) case 1; (b) case 2; (c) case 3; (d) case 4; and (e) case 5.

uncertainties of process inventories in the LCA results. The process inventories with sensitivity over 10% include asphalt pavement-raw materials, raw materials' production-petroleum asphalt, raw materials production-modified asphalt, asphalt pavement-asphalt mixture production, and asphalt pavement-maintenance, of which the uncertainty of these process inventories is 5.59, 11.46, 11.46, 10.00, and 10.31, respectively. Due to the LCI data of asphalt collected from different databases, the productions of petroleum asphalt and modified asphalt have higher uncertainty than other unit process inventories. Therefore, to improve the accuracy of results in an LCA project, the database should be settled or collect the data from the field directly. In addition, the uncertainties of all processes are smaller than 15%. It indicates that the results in this study are relatively credible.

Table 6: The sensitivity of GWP, CADP, and PMF with the corresponding unit process.

Unit process-inventory	GWP		CADP		PMF	
	HMA	WMA	HMA	WMA	HMA	WMA
Asphalt pavement-raw materials	56.56	65.70	74.88	77.04	41.28	50.10
Raw materials' production-petroleum asphalt	36.50	41.22	50.57	51.27	20.95	23.93
Petroleum asphalt production-raw petroleum	35.23	39.79	59.45	60.28	12.51	14.29
Asphalt pavement-asphalt-mixture production	24.88	14.72	—	—	28.37	17.03
Asphalt-mixture production-CO_2 emission	18.18	—	—	—	—	—
Raw materials' production-modified asphalt	15.75	17.79	19.42	19.68	11.18	12.78
Modified asphalt production-raw petroleum	11.33	12.80	19.13	19.39	—	—
Asphalt pavement-maintenance	10.75	10.76	11.30	11.32	—	—
Asphalt pavement-end of life	—	—	—	—	11.31	12.92

4. Conclusions

In this study, a comparative comprehensive life cycle assessment (LCA) was conducted for WMA and HMA pavements. The LCA of the pavement model was established, which includes the stages of raw materials' production, asphalt-mixture production and transportation, maintenance, and disposal at the end of life. The inventories of every unit process were collected and analyzed. Since the long-term performance of WMA pavement has not been well understood, five maintenance scenarios were assumed to assess the environmental impacts of WMA and HMA pavements. The specific conclusions can be drawn as follows:

(1) The results suggest that, assuming comparable long-term performances with that of HMA pavement, WMA pavement produces less CO_2 and $PM_{2.5}$ emissions during their entire life cycle, which indicates that WMA pavement is friendlier for environment.

(2) The assessment reveals that the difference in Chinese Abiotic Depletion Potential (CADP) between WMA and HMA pavements could be negligible, which indicated that WMA pavement technique consumes almost the same resource as that of HMA pavement during the entire service life.

(3) The sensitivity assessment results indicated that improving the technology in raw material production is the most effective way to reduce the environmental impacts for both WMA and HMA pavements.

Data Availability

In this paper, all the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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