

Energy Consumption and Carbon Emissions in Asphalt Pavement Construction: A Lifecycle Assessment of a Modular Approach

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Asphalt mixtures are widely used composite materials in pavement engineering, and their evaluation increasingly requires consideration of both functional performance and environmental sustainability. This study develops a modular lifecycle assessment (LCA) framework to quantify energy consumption and carbon emissions as additional performance indicators of asphalt mixtures in China. By standardizing unit processes, the framework integrates raw material production, processing, transportation, and construction, enabling efficient and reproducible evaluation of material-related impacts. Comparative results demonstrate that stone mastic asphalt (SMA) mixtures consume 2.6 times more energy and release 1.6 times more carbon emissions than asphalt concrete (AC) mixtures under identical pavement structures. Raw material production and mixing dominate the environmental footprint, contributing 87–96 % of energy use and over half of total emissions, while transportation distances further influence material performance. The proposed modular approach, through parameterized modeling and data reuse, enhances the efficiency and accuracy of environmental assessment. By establishing energy and carbon intensity as measurable attributes of asphalt mixtures, this study expands conventional material evaluation beyond mechanical and durability properties, providing a new perspective for the selection and optimization of pavement materials.

Keywords: asphalt mixtures, composite materials, lifecycle assessment, carbon emissions.

1. INTRODUCTION

With the continuous rise in greenhouse gas (GHG) emissions and global temperatures, the greenhouse effect has become a critical environmental concern [1]. The road construction industry, a major contributor to GHG emissions, faces significant challenges in emission reduction [2]. Carbon emissions, a major driver of the greenhouse effect, refer to CO₂ released by human activities such as fossil fuel combustion (coal, oil, natural gas), industrial production, and deforestation [3]. Identifying carbon sources is crucial for accurate carbon emission calculations in asphalt pavement construction, and their classification varies based on different organizational methods [4, 5]. Studies indicate that carbon emissions in road construction primarily stem from mechanical fuel consumption and emissions generated by electricity and heat energy during raw material production and processing [6]. Indirect emissions, including those from human activities, are generally excluded from the accounting scope [7].

Lifecycle assessment (LCA) is widely used to evaluate the environmental benefits of road projects [8, 9]. Wang et al. [10] applied LCA to demonstrate that incorporating incinerated garbage slag in road construction effectively reduces carbon emissions. Santos et al. [11] proposed an LCA model that integrates material production, construction, use, and maintenance stages, forming a comprehensive lifecycle analysis framework. Batouli et al.

[12] integrated LCA with lifecycle cost analysis (LCCA) to assess its decision-making value in sustainable pavement selection. Butt et al. [13] developed a method for allocating energy consumption in asphalt binders, while Yash [14] proposed refinements to the evaluation system for paving materials, improving calculation accuracy in specific processes. Santero et al. [15] identified limitations in existing LCA methods, particularly in phase boundary definitions and data standardization.

Scholars have investigated the effects of pavement structure, construction techniques, and machinery selection at the technical application level. Cao et al. [16] compared the ecological efficiency of hot recycling and milling resurfacing techniques, demonstrating their impact on carbon emissions. Wang et al. [17] quantified emission differences in material production and construction by comparing rubber asphalt with traditional pavements. Liu et al. [18] developed a framework to evaluate the impact of pavement design on lifecycle carbon emissions, while Santos [19] validated this methodology through a multi-tool comparative study. Chen [20] analyzed how pavement structure and material properties influence indirect carbon emissions during the usage phase.

The lifecycle assessment (LCA) framework established by the International Organization for Standardization (ISO) consists of four stages: goal definition, inventory analysis, impact assessment, and interpretation [21]. Chan [22] was the first to integrate LCA with full lifecycle cost evaluation, achieving economic and environmental synergies by

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monetizing environmental costs. Park et al. [23] developed an IO-LCA hybrid model to assess the material stage using the South Korean economic input-output model. Treloar et al. [24] applied an integrated LCA approach to analyze the environmental impacts of various pavement structures. Wu [25] categorized asphalt road construction into three stages and introduced a calculation method using standard coal (kg/t) and CO₂ equivalent (kg/t). Current research continues to encounter challenges related to complex and redundant calculation methods [26–29].

To address these challenges, this study introduces a modular carbon emission calculation method for asphalt mixtures in China. Unlike conventional approaches that often emphasize project-level management, the proposed framework is designed as a material-oriented evaluation tool. By treating energy consumption and carbon intensity as quantifiable attributes of asphalt mixtures, alongside their established mechanical and durability properties, the method mitigates data heterogeneity, eliminates redundant calculations, and enhances reproducibility. This modular framework therefore provides a new perspective for the comprehensive assessment and optimization of pavement composite materials.

2. METHODS AND THEORIES

Defining the material and energy input inventory in pavement construction is essential for accurate carbon emission quantification. Current research commonly employs the budget quota method, which requires extensive mechanical and product inputs, resulting in redundant data processing. To enhance the efficiency of traditional lifecycle assessment (LCA) inventory analysis, this study incorporates modularization and develops an input inventory for each stage of pavement construction. Baldwin [30] stated that modular design breaks down product elements into independent subsystems, allowing complex products or processes to be assembled from standardized modules. LCA comprises four key stages: goal and scope definition, inventory analysis, impact assessment, and interpretation, as illustrated in Fig. 1. Different countries use various inventory databases based on factors such as energy structure, industrial development, and other considerations. Examples include the IPCC Emission Inventory Guidelines, the CLCD of China, and the Ecoinvent of Switzerland.

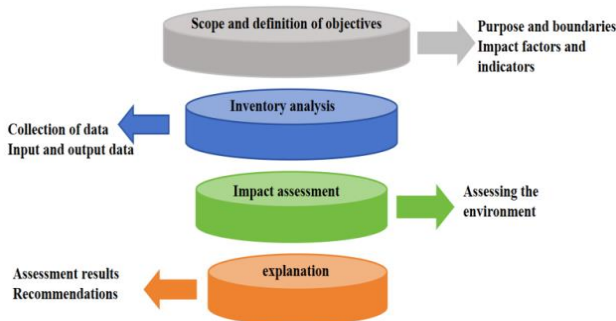


Fig. 1. LCA evaluation process

The inventory analysis stage involves calculating and collecting data on emissions from raw materials, energy, and other inputs. It mainly consists of two aspects: collecting and calculating energy consumption and carbon

emissions inventories. Energy consumption for raw material and energy production is calculated using the net calorific value method. The annual greenhouse gas inventory reporting system of the IPCC provides net calorific values for different energy sources, as shown in Eq. 1. Net calorific value can be converted into energy consumption. In the lifecycle assessment model for raw material production, total energy consumption is calculated using formula [31].

$$E_e = \sum_{i=1}^n (Fuel_i \times NCV_i), \quad (1)$$

where NCV_i is the net calorific value of the fuel; i is the type of fuel.

Carbon emissions from raw material production and energy consumption are calculated using the emission factor method, and the calculation formula is shown in Eq. 2. In the lifecycle assessment model, total carbon emissions during the raw material production phase are calculated using formula [32].

$$E_j = A \times EF, \quad (2)$$

where A is the activity quantity; EF is the carbon emission factor.

Energy consumption and carbon emissions in asphalt pavement are influenced by multiple factors, including raw materials, pavement structure, and construction equipment. Traditional methods rely on complex data collection and specialized software, with results varying due to differences in national standards [33, 34]. This study proposes a novel modular calculation method that addresses the limitations of traditional lifecycle assessment (LCA).

This innovative approach uses a standardized unit of 1000 m³/m², integrating the LCA framework with modular design. By analyzing energy and material flows, the method enables rapid carbon emission quantification. The system boundary encompasses the entire process, including raw material production, processing, transportation, energy use, and construction, addressing data redundancy caused by stage-based calculations (e.g., raw material production, mixing, paving) in traditional LCA. By fixing the baseline engineering quantity, this method effectively avoids repetitive calculations arising from differences in pavement structure, providing an efficient pathway for carbon emission accounting.

The modular LCA calculation for the asphalt pavement construction phase is shown in Fig. 2. The modular characteristics of asphalt pavement construction enable cross-project reuse of carbon emission calculations. Han [35] utilized BIM technology to modularize highway construction, greatly improving the efficiency of construction quality assessment. Its core is based on asphalt mixture construction, with material and machinery inputs quantified using the China Highway Engineering Budget Quota and the Machinery Shift Cost Quota. This is combined with a shift-to-fuel conversion model to generate inventories of material and energy consumption. By integrating the material processing steps, energy consumption and emissions during collection and processing are simultaneously accounted for. Finally, carbon emission data from material production, processing, storage, transportation, and construction are accumulated throughout the process to form the total module value. This method relies on process iteration and data matching

(unit/baseline flow) to rapidly generate standardized emission inventories for the entire process.

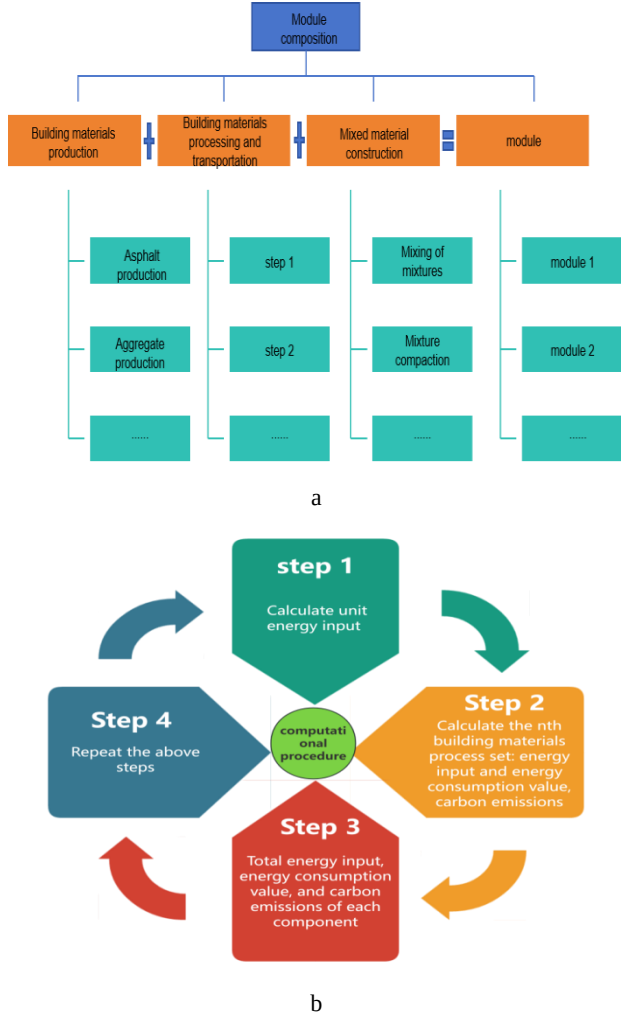


Fig. 2. Modular calculation method of LCA: a–modular system boundary; b–modular calculation steps

The modular calculation for pavement construction in road engineering encompasses the entire process, including asphalt mixture raw material production, processing, transportation, and construction. Design parameters (e.g., oil-stone ratio, mix ratio, compaction degree) directly affect the amount of raw materials used. Due to the complexity and scale of tracking energy consumption and carbon emissions across multiple production stages, this study evaluates the environmental impact of material production using environmental emission inventory analysis. The raw material quantification method, which utilizes parameters such as pavement thickness and core density, offers a theoretical foundation for data calculations.

$$m_i = \rho s d \frac{p_i}{\sum p} \quad (3)$$

where m_i represents the amount of the i -th raw material in t; P is the material's theoretical density in kg/m^3 ; s is the material area in m^2 ; d is the design thickness in meters, and P_i is the proportion of the i -th material.

For each module, the engineering quantity is u . Energy consumption and carbon emissions during material production and construction for each module are calculated using the following equations:

$$I_u = \sum M_{uj} \times E_{ti} + \sum C_{uk} \times F_k; \quad (4)$$

$$G_u = \sum M_{uj} \times E_{ei} + \sum C_{uk} \times E_k, \quad (5)$$

where I_u is the energy consumption for the production and construction of module materials; M_{uj} is the input amount of the j -th material; E_{ti} is the unit energy consumption of the i -th material; C_{uk} is the number of work shifts for the k -th type of construction machiner; F_k is the unit energy consumption per work shift for the k -th type of construction machinery; G_u is the carbon emissions from the production and construction of module materials; E_{ei} is the emission factor for the i -th type of material; E_k is the emission factor for the k -th type of construction energy used.

The values and units of M_{uj} and C_{uk} are derived from the "Highway Engineering Budget Quota" of China, the values of F_k are calculated using the "Highway Engineering Machinery Work Shift Cost Quota" of China, and the values of E_{ti} and E_{ei} are provided in the carbon emission factor list below. This formula calculates the energy consumption and carbon emissions associated with the production of materials for each module. The calculation methods for modular energy consumption and carbon emissions in asphalt pavement construction, building material production, and processing are clarified based on the calculation formulas and models.

Assuming asphalt pavement construction consists of n modules, each of which includes an asphalt mixture construction unit process, along with multiple material production, processing, and mixture production steps. In road engineering, energy consumption and carbon emissions from material production, processing, asphalt mixture transportation, and construction for each unit are accumulated to obtain the total energy consumption and environmental emissions. The formula is given below.

$$I = \sum_n M_{ji}; \quad (6)$$

$$G = \sum_n M_{jG}, \quad (7)$$

where I is the total energy input for pavement construction; G is the total carbon emissions for pavement construction; M_{ji} is the energy input for the j -th module; M_{jG} is the carbon emissions for the j -th module.

The calculation of carbon emissions for asphalt pavement construction involves various machinery types and large datasets. The traditional Life Cycle Assessment (LCA) method divides the construction process into stages and calculates energy consumption and carbon emissions for each stage based on data such as engineering quantities, construction quotas, and machinery work shifts using different formulas. However, this method increases complexity due to the repeated calculation of unchanged data. As shown in Fig. 3 a, to simplify the calculation, this section divides the construction process into units, where each unit independently calculates energy input and carbon emissions. Furthermore, engineering quantity data is introduced to create a database linking unit engineering quantities, energy consumption, and carbon emissions, applicable to different roads, optimizing the calculation process and avoiding redundant calculations, as shown in Fig. 3 b. The traditional carbon emission calculation approach and the unit-based engineering calculation approach are shown in Fig. 3.

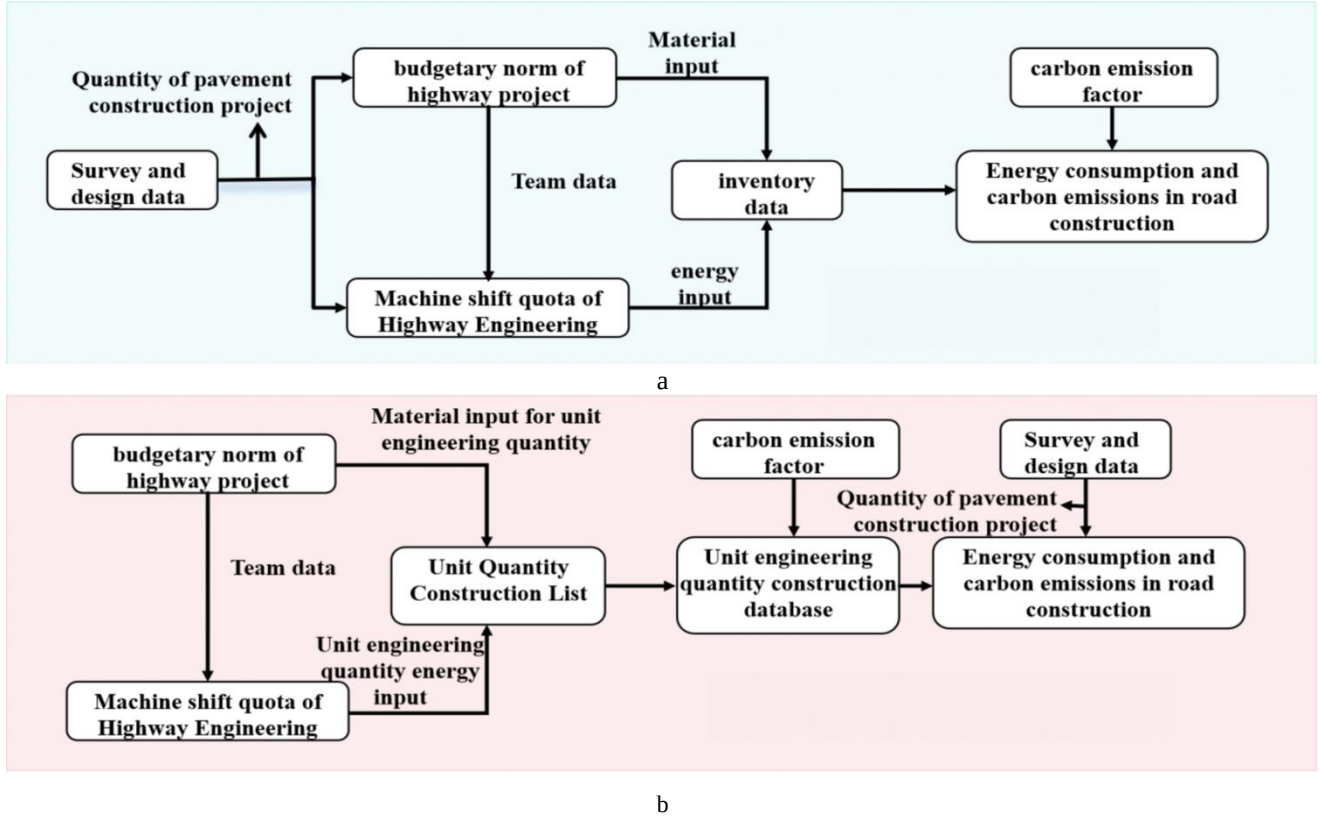


Fig. 3. Comparison of two calculation paths: a – tradicional carbon emission calculation path; b – calculation path for carbon emissions of unit engineering quality

As an example, the production input-output for 1000 m³ of AC-13 asphalt mixture is selected as the calculation unit, referred to as a primitive. This primitive includes the production and processing stages of raw materials, such as asphalt, aggregates, and mineral powder, but excludes stages like paving, rolling, and asphalt spraying. Therefore, only energy consumption and carbon emissions during the raw material input stage are considered in the calculation. Asphalt pavement construction consists of multiple primitives, covering stages like mixture production, paving, and rolling. By determining the number of primitives and their input list in pavement construction, corresponding calculation formulas can be established to quantify total energy consumption and carbon emissions.

$$A = \sum_j^n A_{Ij} \times a_j; \quad (8)$$

$$I = \sum_j^n E_{Ij} \times a_j; \quad (9)$$

$$G = \sum_j^n E_{Gj} \times a_j, \quad (10)$$

where A is the total material and energy input; I is the total energy consumption; G is the total carbon emissions; A_{Ij} is the energy input for the j -th module and its raw materials; a_j is the number of primitives in the j -th module; E_{Ij} is the energy consumption for the j -th module primitive; E_{Gj} is the carbon emissions for the j -th module primitive.

3. RESULTS AND DISCUSSION

To meet the engineering project's performance requirements, adjustments to the asphalt mixture proportion and pavement structure design are needed based on aggregate particle size contents and ratios. Asphalt

pavements typically consist of surface, middle, and bottom layers, with each layer using different mixtures, commonly including AC and SMA types. There are significant differences in structure and performance between the two: AC focuses on the uniformity and adhesiveness of asphalt and aggregates, while SMA emphasizes the formation of an aggregate skeleton and resistance to deformation, meeting different engineering needs [36, 37]. Variations in parameters during the proportion design phase and the mixture type both affect the energy consumption and carbon emissions of raw material production [38]. Based on common highway pavement structures, Table 1 lists key parameters for AC and SMA asphalt mixtures, including asphalt blending ratios, aggregate gradation, and mixture density.

Using the parameters of the asphalt mixture in the above table, the raw material input is determined for 1000 m³ of asphalt pavement construction. Using the raw material input and the carbon emission factors in Table 2, the energy consumption and carbon emissions in the raw material production phase for each component of the asphalt mixture are calculated, as shown in Table 3. Table 3 shows significant differences in energy consumption and carbon emissions between AC and SMA asphalt mixtures, which are consistent with the findings of Liu [39] and Thives [40]. Under the same volume and maximum nominal aggregate size, the energy consumption and carbon emissions of SMA mixtures are 2.6 times and 1.6 times those of AC mixtures, respectively. The asphalt content accounts for 8 % to 12 % of the total energy consumption of SMA. The variations in energy consumption and carbon emissions for the two mixtures are as follows: the energy consumption of the AC

mixture is 54386.33–60190.71 MJ, and the carbon emissions are 2029–2248 kg; the energy consumption of the SMA mixture is 123836.3–124908.7 MJ, and the carbon emissions are 2559–2587 kg. The carbon emissions of the two mixtures account for 6.6 % to 12 % of the total

emissions. The main difference lies in the type and yield of asphalt [41, 42]. Asphalt mix design and density parameters are key factors influencing energy consumption and carbon emissions in the raw material production stage.

Table 1. Technical parameters of asphalt mixture

Material type	Asphalt content raatio, %	Aggregate gradation (1#:2#:3#:4#:5#: mineral powder:sand)	Density, g/cm ³
aAC-13	4.5	8:21:23:26:0:6:16	2.351
bAC-13	5.1	8:21:23:26:0:6:16	2.351
cAC-13	5.5	8:21:23:26:0:6:16	2.351
aAC-16	4.3	25:0:30:24:4:17	2.354
bAC-16	4.8	25:0:30:24:4:17	2.354
cAC-16	5.3	25:0:30:24:4:17	2.354
aAC-20	3.5	9:0:12:54:0:6:19	2.358
bAC-20	4	9:0:12:54:0:6:19	2.358
cAC-20	4.5	9:0:12:54:0:6:19	2.358
aAC-25	3.4	17:0:18:25:21:5:14	2.365
bAC-25	4	17:0:18:25:21:5:14	2.365
cAC-25	4.5	17:0:18:25:21:5:14	2.365
aSMA-13	5.5	8:2:40:40:0:10:0	2.353
bSMA-13	6	8:2:40:40:0:10:0	2.353
cSMA-13	6.5	8:2:40:40:0:10:0	2.353
aSMA-16	5.3	12:0:20:58:0:0:10	2.373
bSMA-16	5.8	12:0:20:58:0:0:10	2.373
cSMA-16	6.3	12:0:20:58:0:0:10	2.373

Table 2. List of emission factors for building materials, energy, and electricity

Name	Unit	Net calorific value, MJ/unit	Carbon emission factor, kg CO ₂ /unit
Gasoline	kg	43.124	2.93
Diesel	kg	42.705	3.1
Crude Oil	kg	41.868	3.02
Heavy Oil	kg	41.868	3.17
Matrix Asphalt	t	4649.2	174.24
Modified Asphalt	t	10575.5	295.91
Emulsified Asphalt	t	7898.3	221
Aggregate	m ³	46.55	3.03
Mineral Powder	t	77.85	7.36
Sand	m ³	61.08	2.51
Electricity	kW·h	–	0.9779

Table 3. Raw material consumption, energy consumption, and carbon emissions of 1000 m³ asphalt mixture under different ratios

Material type	Asphalt consumption, t	Aggregate consumption, t	Mineral powder consumption, t	Sand consumption, t	Total energy consumption, MJ	Total carbon emission, kg
aAC-13	105.8	1751.26	134.71	359.23	542480.53	21826.76
bAC-13	119.9	1740.26	133.87	356.98	607744.12	24263.27
cAC-13	129.31	1732.92	133.3	355.47	651253.19	25887.61
aAC-16	101.22	1779.69	90.11	382.97	518836.63	20758.67
bAC-16	112.99	1770.4	89.64	380.97	573305.7	22793.17
cAC-16	124.76	1761.1	89.17	378.97	627774.78	24827.67
aAC-20	82.53	1706.6	136.53	432.34	435444.86	17807.8
bAC-20	94.32	1697.76	135.82	430.1	489990.8	19844.32
cAC-20	106.11	1688.92	135.11	427.86	544536.76	21880.85
aAC-25	80.41	1850.52	114.23	319.84	423680.72	17329.06
bAC-25	94.6	1839.02	113.52	317.86	489343.31	19780.91
cAC-25	106.43	1829.45	112.93	316.2	544062.14	21824.13
aSMA-13	129.42	2001.23	222.36	0	1479149.2	36302.12
bSMA-13	141.18	1990.64	221.18	0	1602932.24	38860.3
cSMA-13	152.95	1980.05	220.01	0	1726821.84	41420.77
aSMA-16	125.77	2022.51	0	224.72	1437954.38	34487.43
bSMA-16	137.63	2011.83	0	223.54	1562810.58	37073.16
cSMA-16	149.5	2001.15	0	222.35	1687771.92	39661.08

Note: a, b, c represent different asphalt dosages.

For example, in studies on asphalt mixture design, it was found that the proportion of various components in the asphalt mixture, such as aggregates, asphalt binder, and additives, as well as the type and quantity of these components, can greatly affect energy consumption and carbon emissions during production [43, 44]. The asphalt mix ratio determines the overall composition of the mixture, which in turn affects processing requirements. A well-optimized mix ratio can lead to a more efficient production process, reducing unnecessary energy use, as Liu Na [45] found that the selection of asphalt mixture plays an important role in the energy consumption and carbon emissions during pavement construction.

The construction of asphalt pavement is divided into three stages: raw material production, processing, and construction. The energy consumption and carbon emissions in the raw material production stage are determined by the pavement design parameters. Praticò [46] demonstrated that the choice of materials and raw materials significantly affects the energy required for production. Meanwhile, the processing stage depends on the initial conditions of raw material processing, such as moisture content and particle size, as emphasized by Liu [47]. In addition, the construction stage is influenced by construction parameters, which can alter energy consumption and emissions [48].

The production of asphalt mixtures involves key processes such as asphalt heating, aggregate drying, and mixture mixing. Previous studies, including Sun's research [49], have shown that asphalt heating is a significant part of energy consumption, with temperature control being a key factor in this process. As Wang [50] found, the design of the pavement structure has a significant impact on energy consumption and carbon emissions. A reasonable pavement design can reduce energy consumption during maintenance and repair processes. However, transportation and raw material processing energy consumption must be determined based on site conditions, as these factors can vary significantly due to differences in local infrastructure and logistics [47].

To minimize parameter errors, this section predefines key parameters, including transportation distance, asphalt heating temperature, and the moisture content of aggregates during the raw material processing. Table 4 presents the temperature range for mixture production with different types of raw materials, highlighting the heating process in hot mix technology. This is consistent with Chong's research [51], which points out that the heating process is one of the most energy-intensive stages in asphalt production.

Table 4. Heating temperature for different types of asphalt mix materials

Type	Aggregate heating temperature, °C	Asphalt heating temperature, °C
AC	175–185	155–165
SBS-AC	190–200	165–175
SMA	190–200	165–175

Aggregate and asphalt heating are critical contributors to energy consumption and carbon emissions in the raw material processing stage. According to the correlation

model between aggregate moisture content and asphalt heating temperature proposed by Lin [31], the energy consumption formula for asphalt mixture mixing and heating is as follows, assuming diesel as the primary energy source:

$$Q = c \times m \times \Delta T, \quad (11)$$

where Q is the energy consumption; c is the specific heat capacity of the material; m is the mass of the material; ΔT is the temperature change. $c_{\text{water}} = 4200 \text{ J/kg} \cdot ^\circ\text{C}$, $c_{\text{steam}} = 1850 \text{ J/kg} \cdot ^\circ\text{C}$, $c_{\text{aggregate}} = 830 \text{ J/kg} \cdot ^\circ\text{C}$, $c_{\text{asphalt}} = 1340 \text{ J/kg} \cdot ^\circ\text{C}$.

Using summer construction in Chongqing as an example, the initial temperatures of both aggregate and asphalt are set to 30 °C. The calculation considers aggregate temperatures ranging from 25 °C to 180 °C and asphalt temperatures from 130 °C to 170 °C. Diesel consumption is determined by correlating energy consumption values with the diesel energy factor in Table 4, while total carbon emissions are calculated using the carbon emission factor.

1. Aggregate drying and heating. Given an aggregate moisture content of 4 %, the total moisture in 1 ton of aggregate is 0.04 tons. Heating energy consumption is categorized into three components: water evaporation ($Q1$), steam loss ($Q2$), and aggregate temperature increase

$$(Q3). Q1 = 4200 \times 40 \times (100 - 25) = 13.23 \text{ MJ};$$

$$Q2 = 1850 \times 40 \times (180 - 100) = 5.92 \text{ MJ};$$

$$Q3 = 830 \times 1 \times (180 - 25) = 0.13 \text{ MJ};$$

$$Q = Q1 + Q2 + Q3 = 19.28 \text{ MJ}$$

2. Asphalt heating: The asphalt heating process excludes moisture evaporation and steam loss factors, focusing solely on the energy consumption and carbon emissions associated with heating the asphalt itself.

$$Q_{\text{asphalt}} = 1340 \times 0.05 \times (170 - 130) = 0.0027 \text{ MJ}$$

Based on the previous calculation results, drying and heating 1 ton of aggregate with a 4 % moisture content consumes 0.62 MJ of energy for each 5 °C temperature increase. The corresponding carbon emissions are 0.000025 kg. Heating 1 ton of asphalt requires 0.00034 MJ of energy for each 5 °C temperature increase, resulting in carbon emissions of 0.000033 kg. Based on the asphalt heating temperature range in Table 4, two heating intervals for asphalt are defined: 30–160 °C and 30–170 °C. The aggregate heating process is influenced by its moisture content. To reduce errors and minimize variable impact, aggregate heating energy consumption and carbon emissions are calculated for heating intervals of 30–180 °C and 30–195 °C, considering 4 %, 5 %, and 6 % moisture content. The selection of construction machinery is presented in Table 5. Table 6 presents the initial settings of various parameters, along with related energy consumption and carbon emission data.

The transportation stage involves the delivery of raw materials to the mixing station and the transportation of asphalt mixtures to the construction site. For calculation simplicity, the transportation of raw materials, including aggregates, mineral powder, and asphalt mixtures, is standardized using 15 t or smaller dump trucks.

Table 5. Equipment list for paving 1000 m³ asphalt pavement

Equipment		Production capacity, t/h/Shift						Energy consumption, MJ	Carbon emission, kg
		30	60	120	160	240	320		
Mixing equipment	320t/h						1.19	686915.58	58003.65
Loader	3m ³ or less						2.52	12429.7236	905.3856
① Dump truck	15t or less						6.91	20033.75	1454.28
② Dump truck	30t or less	3.88						14929.15	1083.72
Paver, t	6			3.96				7885.67	572.42
	9				2.79			11520.33	836.27
	12.5					1.86		10820.92	785.50
Roller, t	6–8 t or less						5.46	4507.18	328.31
	9–16 t or less						0.3	1035.17	75.14
	20–25 t or less						2.08	4467.07	325.40
	12–15 t						2.04	3524.79	256.75
Asphalt sprayer, L	8000 or less						0.05	105.42	7.65

Table 6. Raw material parameter settings for each unit element

Project	Basic parameter setting	Energy consumption, MJ	Carbon emissions, kg
Asphalt heating temperature	1 t asphalt heating range 30–160 °C	0.00884	0.000858
	1 t asphalt heating range 30–170 °C	0.00952	0.000924
Aggregate moisture content	1 t aggregate heating range 30–180 °C, moisture content 3 %	13.5	1.32
	1 t aggregate heating range 30–180 °C, moisture content 4 %	18.6	1.8
	1 t aggregate heating range 30–180 °C, moisture content 5 %	22.5	2.16
	1 t aggregate heating range 30–195 °C, moisture content 3 %	14.85	1.452
	1 t aggregate heating range 30–195 °C, moisture content 4 %	20.46	1.98
	1 t aggregate heating range 30–195 °C, moisture content 5 %	24.75	2.232

Table 7. Energy consumption and carbon emission calculations for asphalt mix with different transport distances (per 1000 m³)

Project	Transport machinery	Transport distance, km	Energy consumption, MJ	Carbon emission, kg
Transport distance	15 t or less dump truck	1	20033.75	1454.28
		10	50301.81	3651.48
		20	83933.00	6092.82
		50	184826.55	13416.83
		100	352982.47	25623.51
		200	689294.31	50036.87
		500	1698229.83	123276.95

Taking asphalt mixture transportation as an example, the transportation distances are categorized into seven groups, ranging from 1 km to 500 km. Table 7 presents the energy consumption and carbon emission calculations for various transportation distances.

The results in Table 6 and Table 7 show that the asphalt mixture construction process is notably affected by factors like raw material processing and transportation distance. In the raw material processing stage, energy consumption and carbon emissions from heating aggregates are more significant than those from heating asphalt, mainly due to the aggregate moisture content and heating temperature. This finding supports Liu research [52], which highlighted that aggregate processing is a key stage for energy consumption and carbon emissions, as heating and drying aggregates account for 90 % of total energy use.

In the transportation stage, transportation distance significantly impacts energy consumption and carbon emissions. Previous studies, such as Chai research [53], emphasized that transportation distance is a key factor in determining both energy consumption and carbon emissions. The longer the transportation distance, the more energy is required for transportation, resulting in higher carbon emissions. As Acevedo [54] noted, optimizing transportation logistics is crucial for minimizing the

environmental impact of pavement construction. Transportation distance is a key factor in controlling the energy consumption and carbon emissions of asphalt mixture production. Fernandes [55] confirmed this, concluding that the transportation stage accounts for a significant portion of total energy consumption and emissions, and should not be overlooked.

The LCA modular calculation decomposes the asphalt pavement construction process into several reusable modules, with each module represented as a primitive. Based on the energy consumption and carbon emission data from the previous section, it is clear that the asphalt mixture design parameters and raw material processing parameters significantly affect the total energy consumption and carbon emissions of the asphalt pavement construction process. To aid in subsequent calculations, the initial parameter settings for each primitive are presented in Table 8. Based on the construction stages of asphalt pavement, it is divided into the elements listed in the table below, with the engineering quantities for each element provided in Table 9. The parameter settings for calculating the energy consumption and carbon emissions of engineering elements are based on the initial data from Table 3, Table 6, and Table 7. The calculation results are presented in Table 9.

Table 8. Initial parameter settings for each unit element

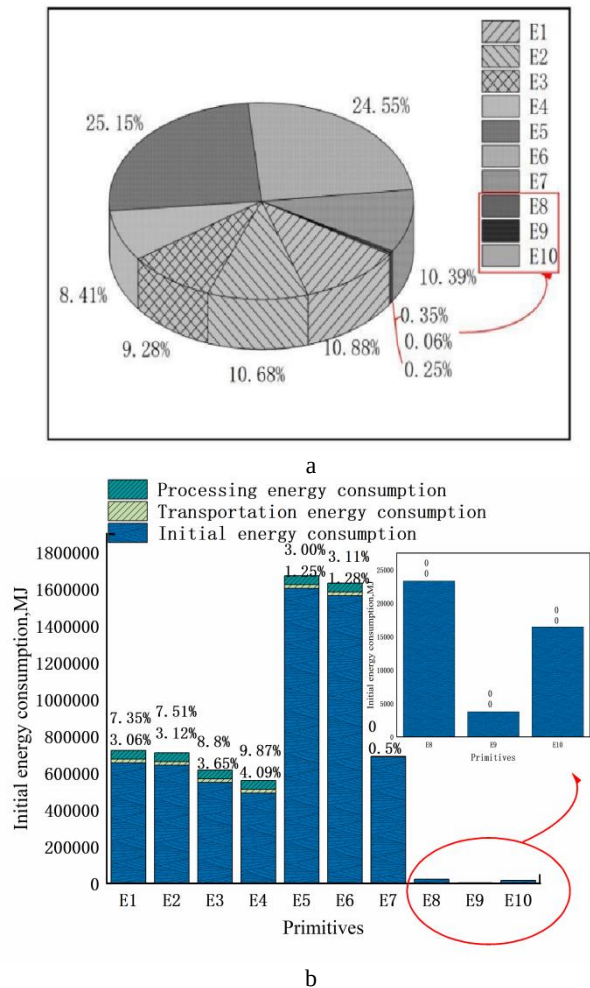
Parameter type	Parameter setting
Mix design Parameters	Consider asphalt content and density of the asphalt mixture. Select the B-type asphalt mixture parameters from the technical parameters table.
Parameter type	Parameter Setting
Raw material and mixture transport	Transport aggregate, sand, mineral powder, and asphalt mixture. The initial setting is that the distance from the material processing locations to the mixing plant is 1 km. Use a 15 t or smaller dump truck.
Material processing	Aggregate moisture content 4 %, heating temperature range 30 – 195 °C. Asphalt heating range 30 – 170 °C.

Table 9. Unit element energy consumption calculation values, MJ

Element	Engineering quantity	Excluding transportation and material processing	①Including transportation	②Including material processing
E1	1000 m ³ AC-13	607744.12	674708.82	702776.73
E2	1000 m ³ AC-16	573305.7	661590.23	689719.32
E3	1000 m ³ AC-20	489990.8	568171.76	596382.69
E4	1000 m ³ AC-25	489343.31	510234.58	538588.73
E5	1000 m ³ SMA-13	1602932.24	1622966	1651074.63
E6	1000 m ³ SMA-16	1562810.58	1582844.33	1611362.16
E7	1000 m ³ mixing asphalt	686915.58	690364.74	686915.58
E8	1000 m ³ asphalt paving	23319.96	23319.96	23319.96
E9	1000 m ² tack coat spraying	3770.23	3770.23	3770.23
E10	1000 m ² seal coat spraying	16462.14	16462.14	16462.14

Based on the analysis of Table 9, the total energy consumption of asphalt pavement construction is primarily influenced by the mixing and raw material production stages, accounting for approximately 87 % to 96 %, with the energy consumption from machinery during transportation having a lesser impact. These findings align with Liu research, which highlights that the asphalt mixing and material processing stages are dominant in terms of energy consumption, primarily due to the heating and mixing requirements [47]. The transportation process of raw materials in the asphalt mixture production stage accounts for 1 % to 4 % of the total energy consumption of raw material production, while the transportation processes in the paving and spraying stages contribute nearly zero. In comparison to the transportation segment, the raw material processing stage consumes more energy, with the majority of energy consumption occurring during the processing phase between raw material production and mixture mixing. The raw material processing in each primitive of the raw material production process contributes 3% to 9% to the total energy consumption of raw material production, excluding transportation.

The Fig. 4 illustrates the energy consumption distribution for each primitive, where "initial energy consumption" refers to the energy consumption of the primitive, excluding transportation and raw material processing. Fig. 4 a shows that, during the raw material production stage of asphalt pavement, the initial energy consumption of modules E5 and E6 accounts for about 50 % of the total energy consumption of the primitives. Compared to modules E1, E2, E3, and E4, their energy consumption share is significantly higher. This indicates that, under the same volume conditions and excluding transportation and raw material processing, the energy consumption for producing AC-type asphalt mixture raw materials is nearly 50 % lower than that of SMA-type asphalt, making the raw material production process more energy-efficient for AC-type asphalt.

**Fig. 4.** Energy consumption proportion of unit elements: a—proportion of unit element energy consumption; b—comparison of energy consumption under different conditions

This is primarily due to the higher energy consumption involved in the production of modified asphalt. Additionally, the energy consumption of the asphalt mixture mixing process is comparable to the proportion of raw material production in the total energy consumption of asphalt pavement construction. Fig. 4 b shows the proportion of energy consumption and carbon emissions from the transportation and raw material processing stages relative to the initial energy consumption and carbon emissions. The top and bottom rows represent the contributions from the transportation and raw material processing processes, respectively. Analysis of Figure 4(b) reveals that, under the predetermined initial parameters, the impact of raw material processing and material transportation on modules E1-E6 is more significant compared to modules E7-E10. However, the overall impact on total energy consumption is minimal.

Based on the modular calculation model, carbon emission values for each primitive have been calculated. The engineering quantities and corresponding carbon emission values for each primitive are presented in Table 10. The analysis of Table 10 indicates that the total carbon emissions for asphalt pavement construction are less influenced by emissions from transportation machinery and equipment, and more significantly impacted by the mixing and raw material production processes, together accounting for over 50 % of the total emissions. Specifically, during the raw material production stage for the asphalt mixture, carbon emissions from material transportation contribute 0.4 % to 8 % of the total carbon emissions in raw material production. In the material processing stage, this contribution ranges from 11 % to 24 %. During the asphalt paving and spraying stages, carbon emissions from the transportation process are negligible. Compared to transportation, the raw material processing stage has a more substantial effect on energy consumption, with raw material processing accounting for 3 % to 9 % of the total energy consumption (excluding transportation) in raw material production.

Based on Table 10, a pie chart illustrating the carbon emissions of each primitive is created, as shown in Fig. 5. The term "initial carbon emissions" refers to the carbon emissions of the primitives, excluding those from transportation and raw material processing. Fig. 5 a illustrates that, during the raw material production stage of asphalt pavement, modules E5 and E6 contribute to

approximately 33 % of the total initial carbon emissions, a proportion that is relatively high compared to modules E1, E2, E3, and E4.

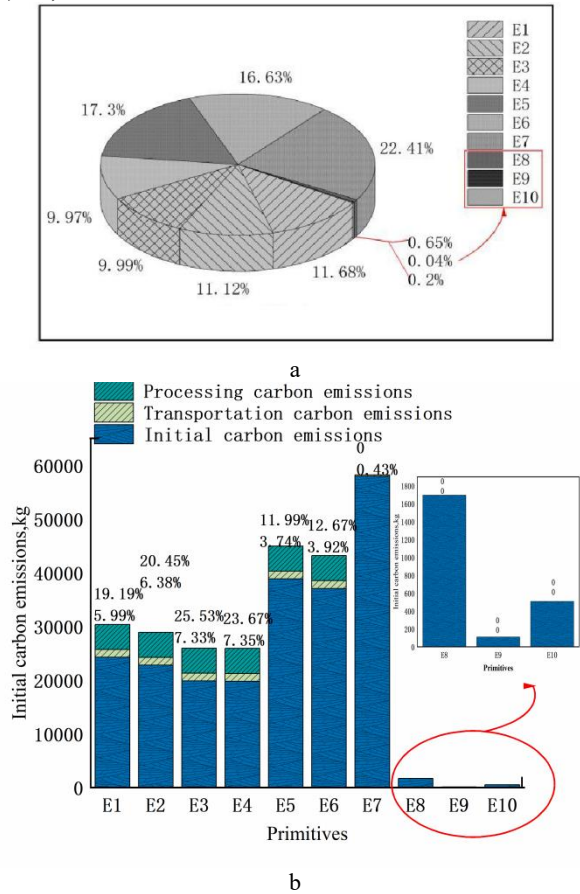


Fig. 5. Unit element carbon emissions: a—carbon emission proportion of unit elements; b—comparison of unit element carbon emissions under different conditions

This suggests that, under the same volume conditions, the carbon emissions from the raw material production of AC-type asphalt mixture are approximately 40 % lower than those of SMA-type, primarily due to higher emissions from modified asphalt production. Additionally, the mixing of the asphalt mixture contributes the most to the total carbon emissions during the asphalt pavement construction process, accounting for approximately 22 %. In Fig. 5 b, the upper and lower rows of numbers represent the proportions of carbon emissions from the transportation process and raw material processing, respectively.

Table 10. Unit element carbon emission calculation values, kg

Element	Engineering quantity	Excluding transportation and material processing	①Including transportation	②Including material processing
E1	1000 m ³ AC-13	24263.27	25717.55	28918.27
E2	1000 m ³ AC-16	22793.17	24247.45	27454.09
E3	1000 m ³ AC-20	19844.32	21298.6	24513.16
E4	1000 m ³ AC-25	19780.91	21235.19	24463.61
E5	1000 m ³ SMA-13	38860.3	40314.58	43519.24
E6	1000 m ³ SMA-16	37073.16	38527.44	41771.7
E7	1000 m ³ asphalt mixing	58003.65	58254.03	58003.65
E8	1000 m ³ asphalt paving	1695.96	1695.96	1695.96
E9	1000 m ² tack coat spraying	110.19	110.19	110.19
E10	1000 m ² seal coat spraying	507.64	507.64	507.64

Analysis of Fig. 5 b reveals that, under the initial parameter settings, the impact of raw material processing and material transportation on modules E1 to E6 is more pronounced than on modules E7 to E10. However, their overall impact on total carbon emissions is minimal.

4. CONCLUSIONS

This study proposes a modular lifecycle assessment (LCA) method for evaluating energy consumption and carbon emissions of asphalt mixtures. The method integrates raw material production, processing, transportation, and construction through standardized units (1000 m³/m²), improving efficiency and avoiding redundancy in assessment. Results show that stone mastic asphalt (SMA) mixtures consume 2.6 times more energy and emit 1.6 times more carbon than asphalt concrete (AC) mixtures, mainly due to modified binders and more complex production processes. Raw material production and mixing dominate the footprint, while aggregate heating is affected by moisture and temperature, and transportation distance shows a linear correlation with emissions. The modular LCA method establishes energy use and carbon footprint as measurable attributes of asphalt mixtures, supporting material comparison, selection, and sustainable optimization.

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