Prediction model for energy consumption and carbon emission of asphalt surface construction

Zheng Zhang1*, Xujun Gao 2, Jiafei Wang 2 and Xiaoping Ji 1

1 Key Laboratory of Highway Engineering of Ministry of Education in Special Areas, Chang'an University, Xi'an, Shanxi, 710043, China.
2 Northwest Survey and Design Institute Co., Ltd of China Power Construction Group, Xi'an, Shanxi, 710065, China.

*Corresponding author’s e-mail: 17606218924@163.com

Abstract. The construction of asphalt surface layer will generate a lot of energy consumption and carbon emissions. In order to realize the energy-saving and low-carbon construction of asphalt pavement, it is of positive significance to establish a calculation model for energy consumption and carbon emission of asphalt surface layer construction. This paper uses the LCA method to establish a calculation model for estimating the energy consumption and carbon emission of asphalt surface layer construction through data query and construction site analysis. It uses the example calculation to analyze the key links of construction energy consumption and carbon emission and proposes effective Low carbon construction technology. The results show that the three processes of mixture transportation, asphalt de-barrel heating, aggregate drying and heating are the key links in the whole asphalt surface construction process. Warm mix construction technology and control of aggregate moisture content technology can effectively reduce construction energy consumption and carbon emissions.

1. Introduction
Road construction is the hardest hit area for energy consumption and carbon emissions. It relies heavily on building materials such as earth, stone, lime, cement and asphalt. A large number of studies have shown that the traditional asphalt pavement construction process will generate a large amount of energy consumption and carbon emissions, which is not conducive to environmental protection and sustainable development of the construction site[1-3]. In view of this, it is highly desirable to develop a systematic calculation model to accurately estimate energy consumption and carbon emissions during asphalt pavement construction. It not only helps to assess the energy consumption and carbon emissions and the influencing factors in the construction process, but also provides a basis for reducing road construction energy consumption and carbon emissions by revealing and studying these influencing factors.

At the end of the last century, relevant scholars have analyzed and evaluated the energy consumption and carbon emissions of pavements, and obtained some positive and beneficial results by referring to the calculation method of the Life Cycle Analysis (LCA) [4-7]. Pablo Zapata et al. [8] established LCA models and proposed that in sustainable design work, the work of reducing energy consumption is best carried out in the initial stage of the pavement life cycle. Qazi Aurangzeb et al. [9] considered the material, construction, maintenance and repair phases of the pavement life cycle. The
results show that during the entire life cycle of the pavement, the contribution of energy consumption during the construction phase is minimal, and the energy consumption of raw materials has an important impact on the total energy consumption. Yang, Zhang et al. \[10,11\] established a basic framework for energy consumption and emission estimation of asphalt pavement construction stage through the analysis of energy saving and emission reduction of asphalt pavement, and recommended a method based on quota energy consumption estimation. Li Shouwei \[12\] analyzed the key links and influencing factors of asphalt pavement construction energy consumption and carbon emissions, and established energy consumption and carbon emission benchmarks for asphalt pavement construction. Li Guannan et al. \[13\] conducted a comprehensive analysis of energy consumption and emissions during the materialization, construction, maintenance and maintenance phases of highway asphalt pavement materials.

Based on this, this paper adopts the LCA method to conduct on-site investigation of many highway construction sections in China. The energy consumption and carbon emissions of asphalt mixture production, transportation, paving, rolling and other processes were statistically analyzed to establish an estimated calculation model for energy consumption and carbon emissions of asphalt surface construction. The model is calculated and analyzed by examples, and a low-carbon construction technology that can achieve good energy-saving and emission reduction effects is proposed.

2. Survey analysis and results

2.1. Investigation and Analysis of Construction Process of Asphalt Mixture

(1) The traditional asphalt mixture is hot mix asphalt (HMA). The mixing method of HMA is mainly divided into indirect forced type and continuous drum type. According to the requirements of China's "Technical Specifications for Asphalt Pavement Construction" (JTG F40-2004), this paper mainly studies the energy consumption and carbon emissions of batch mixing equipment. It mainly includes the following four production processes \[14\]: aggregate stacking and cold material loading, asphalt stripping heating, aggregate drying and heating and mixer mixing. According to field investigation and statistics, the energy consumption sources in the asphalt mixture production process are shown in Table 1.

| Production processes                                      | Emission source                        | Fuel type                      |
|----------------------------------------------------------|----------------------------------------|--------------------------------|
| Aggregate stacking and cold material loading              | Transfer machine, scraper              | Diesel                         |
| Asphalt stripping heating                                 | Asphalt heat transfer oil lifting system; | Heavy oil, diesel, coal        |
| Aggregate drying and heating                              | Drying drum; burner;                   | Heavy oil, diesel, coal        |
| Mixer mixing                                              | Mixing building                        | Electric energy                |

(2) The transportation of HMA not only generates a large amount of fuel consumption, but also ensures that HMA does not cause segregation due to excessive transportation time. Therefore, it is necessary to investigate and calculate the transportation distance, load and fuel consumption of different transport vehicles. Table 2 summarizes the energy consumption benchmarks of the transport machinery on the site surveyed.

| product name | Vehicle model | Traffic volume | Comprehensive fuel consumption (L/100km) | Energy equivalent (MJ/t km) |
|--------------|---------------|----------------|------------------------------------------|-----------------------------|
| Dump truck   | HFC3252KR1K3  | 13             | 20.3                                     | 0.58                        |
|              | ND32500B38J7  | 13             | 22.4                                     | 0.65                        |
|              | BDD3250BJ60Q  | 13             | 24.0                                     | 0.69                        |
|              | LZ325OPDG     | 13             | 24.0                                     | 0.71                        |
|              | DFV3310G      | 16             | 27.6                                     | 0.63                        |
|              | EQ3259GF      | 13             | 23.8                                     | 0.67                        |
HN3201Z21C2N3   10  23.2  0.84
HFC5202XQYKR1LT   10  28.8  1.06
ALA5310GFLB3     15  31.8  0.79
DQJ5258GGSNB     12  29.1  0.87
ND42500B32J      24  38.5  0.59
DYX5250GSS38YP    13  28.2  0.81
CXQ5250GRYHFC    15  27.6  0.68
ALA5310GYYDFL3    20  31.9  0.59
CGC1250PA41WPD3C  15  28.3  0.67

General transport vehicle  —  —  0.81
ALAX5250GJBDFL3   11  29.1  0.98
BJ5253GJB-2      10  29.2  1.05
CLY5317GJB5      14  31.4  0.82

Concrete mixer truck
AH5250GJB1       12  30.1  0.79
TZ5257GJBZ4N     30  50.0  1.31
CTY5251GJBZ5     14  30.2  0.79
HDJ5251GJBHII    13  28  0.73

(3) The types of pavers commonly used for asphalt paving are mainly [15]: Volvo ABG8820B crawler asphalt paver, XCMG RP952 asphalt paver, Sany Heavy Industry SAP900CD high grade asphalt paver. It mainly investigates the fuel consumption of its paving unit volume asphalt mixture. Table 3 summarizes the operating parameters of several pavers.

Table 3. Paver parameters

| Power (kw) | Maximum working capacity (t/h) | Unit consumption (g/kw.h) |
|------------|--------------------------------|--------------------------|
| 140        | 300                            | 190                      |
| 130        | 240                            | 205                      |
| 137        | 800                            | 189                      |
| 136        | 400                            | 190                      |
| 51.1       | 280                            | 190                      |
| 35.5       | 100                            | 190                      |
| 176        | 900                            | 189                      |
| 118        | 600                            | 208                      |

(4) Commonly used roller compactors for asphalt surface rolling include steel wheel compactors (Vegele, Boman, etc.) and rubber roller compactors (Xugong). The main investigation is the fuel consumption of compacting unit volume of asphalt mixture. Table 4 summarizes the operating parameters of several road rollers.

Table 4. Road roller parameters

| Rated power (kw) | Unit consumption (g/kw.h) |
|-----------------|--------------------------|
| SRS2124S        | 235                      |
| SR26-5          | 228                      |
| SR16            | 210                      |
| SR125           | 190                      |
| SR18m           | 202                      |
| SR22MP          | 223                      |
| SR18M2          | 214                      |
| SR26T           | 210                      |
| SR13D           | 203                      |
2.2. Calculation method of energy consumption and carbon emissions

The construction of asphalt surface layer includes several stages of production, transportation, paving and rolling of asphalt mixture. The energy types of each stage are different, and the corresponding energy consumption is also different. A uniform standard needs to be established to calculate the total energy consumption of the asphalt mixture.

Therefore, this paper uses the net calorific value to calculate the energy consumption and uses the carbon emission coefficient to calculate the carbon emissions. By collating the statistical data in the China Energy Statistical Yearbook 2008, the net calorific value and carbon emission coefficient of energy consumed by machinery and transportation vehicles during the construction of asphalt mixture are obtained, as shown in Table 5.

| Fuel type          | Carbon emission coefficient | unit | Heating coefficient | unit |
|--------------------|----------------------------|------|---------------------|------|
| Heavy oil          | 2.9                        | kg/l | 35.8                | MJ/l |
| Diesel             | 2.7                        | kg/l | 36.7                | MJ/l |
| Gasoline           | 2.2                        | kg/l | 32.6                | MJ/l |
| Kerosene           | 2.5                        | kg/l | 35.5                | MJ/l |
| Natural gas        | 2.1                        | kg/m³| 51.4                | MJ/m³|
| Standard coal      | 2.6                        | kg/Kg| 21.9                | MJ/Kg|
| Electric energy    | 0.69                       | kg/kW.h| 3.6                | MJ/kW.h|

From the production to the construction process, the asphalt mixture needs to consume a variety of energy sources. This is a direct source of carbon emissions. The energy consumption of each stage must be calculated. The energy consumption calculation model is shown below.

\[ m_{E,j} = \sum_i m_{E,ij} \quad (1) \]

Where \( m_{E,j} \): The sum of the energy consumption of the jth energy in each construction stage, kg; \( m_{E,ij} \): The j-th energy consumption in the construction phase i, kg.

Convert the consumption of different energy sources into calorific value to get the total energy consumption:

\[ EC = \sum_j m_{E,j} q_j \quad (2) \]

Where EC: Total energy consumption at each construction stage, MJ; \( q_j \): Heating coefficient of the jth energy source.

Converting the consumption of different energy sources into carbon emissions, and getting total carbon emissions:

\[ QC = \sum_j m_{E,j} p_j \quad (3) \]

Where QC: Total carbon emissions at each stage of construction, kg; \( p_j \): The carbon emission factor of the jth energy source.

2.3. Survey results

Through the investigation of the expressway surface construction sections of several provinces in China, the energy consumption and carbon emission list of the asphalt surface layer construction process were obtained. After statistical analysis, the energy consumption and carbon emission data were obtained. The results are shown in Table 6 (In the table, jldf means aggregate stacking and cold material feeding, lqtt means asphalt de-barrel heating, jlhg means aggregate drying and heating, bhjd means mixing electromechanical, ys means mixture transportation, tp means mixture paving, ny means mixing material rolling).

| Fuel type       | Project          | jldf(kg/t,) |qtt(kg/t,) | jlhg(kg/t,) | bhjd(kW.h/t,) | ys(kg/km-t, | tp(kg/m3, | ny(kg/m3,) |
|-----------------|------------------|-------------|-----------|-------------|---------------|-------------|------------|------------|
| Diesel          |                  |             |           |             |               |             |            |            |
| Standard coal   |                  |             |           |             |               |             |            |            |
| Heavy oil       |                  |             |           |             |               |             |            |            |
| Electric energy |                  |             |           |             |               |             |            |            |

Table 5. Calorific value and carbon emission coefficient of various energy sources

Table 6. Asphalt surface construction energy consumption and carbon emission list
Road section I 0.175 59.34 6.327 2.64 0.041 0.223 0.983
Road section II 0.181 61.21 6.483 2.50 0.037 0.210 0.707
Road section III 0.155 70.22 5.498 2.74 0.044 0.233 0.785
Road section IV 0.177 68.93 6.996 2.98 0.035 0.255 0.934
Road section V 0.156 63.22 7.001 3.45 0.038 0.243 0.869
Road section VI 0.143 62.58 5.971 2.49 0.045 0.211 0.657
Road section VII 0.156 69.16 6.235 3.15 0.039 0.224 0.779
Average 0.163 64.95 6.36 2.85 0.040 0.228 0.816
Energy
consumption (MJ)
7.1 1422.4 257.5 10.3 1.8 10.0 35.9
Carbon emission (kg)
0.5 100.2 20.9 2.0 0.1 0.7 2.6

3. Prediction model for energy consumption and carbon emission of asphalt surface layer construction

3.1. Establishment of energy consumption prediction model

Combined with Table 6 and field test results, a calculation model for energy consumption of asphalt surface layer construction can be established.

Calculation formula for energy consumption of asphalt surface layer construction:

\[
\sum EC = EC_{\text{qtt}} + EC_{\text{idf}} + EC_{\text{ibg}} + EC_{\text{bhjd}} + EC_{\text{ys}} + EC_{\text{tp}} + EC_{\text{ny}}
\]

\[
EC_{\text{qtt}} = 1422.4m_{l}\text{q}
\]

\[
EC_{\text{idf}} = 7.1m_{jl}
\]

\[
EC_{\text{ibg}} = 257.5m_{jl}
\]

\[
EC_{\text{bhjd}} = 10.3m_{hht}\text{h}
\]

\[
EC_{\text{ys}} = 1.8m_{hht}\text{h}
\]

\[
EC_{\text{tp}} = 10V_{hht}
\]

\[
EC_{\text{ny}} = 35.9V_{hht}
\]

(4)

Where EC_{\text{qtt}}: Energy consumption for asphalt de-bucket heating (MJ); m_{l}\text{q}: Asphalt quality (kg); EC_{\text{idf}}: Energy consumption for aggregate stacking and cold material feeding (MJ); m_{jl}: Aggregate quality (kg); EC_{\text{ibg}}: Energy consumption for aggregate drying and heating (MJ); EC_{\text{bhjd}}: Energy consumption for mixing electromechanical (MJ); m_{hht}\text{h}: Asphalt mixture quality (t); EC_{\text{ys}}: Energy consumption for transportation (MJ); h: Average distance (km); EC_{\text{tp}}: energy consumption for Asphalt mixture paving (MJ); V_{hht}: Compacted asphalt mixture volume (m^3); EC_{\text{ny}}: Energy consumption of the asphalt mixture rolling process (kg).

3.2. Establishment of a carbon emission estimation model

Combined with Table 6 and field test results, a carbon emission calculation model for asphalt surface layer construction was established.

Calculation formula for total carbon emissions from asphalt surface layer construction:

\[
\sum QC = QC_{\text{qtt}} + QC_{\text{idf}} + QC_{\text{ibg}} + QC_{\text{bhjd}} + QC_{\text{ys}} + QC_{\text{tp}} + QC_{\text{ny}}
\]

\[
QC_{\text{qtt}} = 100.2m_{l}\text{q}
\]

\[
QC_{\text{idf}} = 0.5m_{jl}
\]

\[
QC_{\text{ibg}} = 20.9m_{jl}
\]

\[
QC_{\text{bhjd}} = 2m_{hht}\text{h}
\]

\[
QC_{\text{ys}} = 1.8m_{hht}\text{h}
\]

\[
QC_{\text{tp}} = 10V_{hht}
\]

\[
QC_{\text{ny}} = 2.6V_{hht}\text{h}
\]

(5)
Where $Q_{\text{lqtt}}$: Carbon emissions of asphalt de-barrel heating (kg); $m_q$: Asphalt quality (kg); $Q_{\text{jldf}}$: Carbon emissions of aggregate stacking and cold material feeding (kg); $m_j$: Aggregate quality (kg); $Q_{\text{jlhg}}$: Carbon emissions for aggregate drying and heating (kg); $Q_{\text{bhjd}}$: Carbon emissions for mixing electromechanical (kg); $m_{\text{jlhl}}$: Asphalt mixture quality (t); $Q_{\text{ys}}$: Carbon emissions from transportation (kg); $h$: Average distance (km); $Q_{\text{tp}}$: Asphalt mixture paving carbon emissions (kg); $V_{\text{hlhl}}$: Compacted asphalt mixture volume (m$^3$); $Q_{\text{ny}}$: Carbon emissions of the asphalt mixture rolling process (kg).

3.3. Model calculation and analysis

Assume that a 20-kilometer expressway asphalt surface layer has a total of upper, middle and lower surface layers, and the asphalt type, oil-stone ratio and thickness of each surface layer are shown in Table 7.

| Layer         | Material      | Whetstone ratio(%) | Thickness(cm) |
|---------------|---------------|--------------------|---------------|
| Upper layer   | Modified AC-13| 4.9                | 4             |
| Middle layer  | AC-20         | 4.3                | 6             |
| Lower layer   | AC-25         | 4.0                | 8             |

Then, the amount of material required for each surface layer is shown in Table 8 (In the table 8,V$_{\text{hlhl}}$ means the volume of the asphalt mixture, $m_{\text{hlhl}}$ means the quality of the asphalt mixture, $m_lq$ means the asphalt quality, $m_jl$ means the aggregate quality).

| Layer         | $V_{\text{hlhl}}$(m$^3$) | $m_{\text{hlhl}}$(kg) | $m_lq$(kg) | $m_jl$(kg) |
|---------------|---------------------------|-----------------------|------------|------------|
| Upper layer   | 1.93E+04                  | 4.68E+04              | 2.19E+03   | 4.23E+04   |
| Middle layer  | 2.98E+04                  | 7.23E+04              | 2.98E+03   | 6.62E+04   |
| Lower layer   | 3.51E+04                  | 8.51E+04              | 3.27E+03   | 7.85E+04   |
| Total amount  | 8.43E+04                  | 2.04E+05              | 8.44E+03   | 1.87E+05   |

According to the engineering quantity data, the calculation results of the calculation model of the energy consumption and carbon emission of the asphalt surface layer are summarized in Table 9. It can be seen from Figures 1 and 2 that the largest energy consumption and carbon emissions are aggregate drying and heating; although the transportation process consumes less energy, it has a larger proportion of carbon emissions and the energy consumption and carbon emissions of asphalt de-barrel heating are also not negligible. Therefore, the three processes of asphalt mixture transportation, asphalt de-barrel heating, aggregate drying and heating are the key links in the construction process of the entire asphalt surface layer. (In the Table 9 and Figures 1 and 2, lqtt means aggregate stacking and cold material feeding, jldf means asphalt de-barrel heating, jlhg means aggregate drying and heating, bhjd means mixing electromechanical, ys means mixture transportation, tp means mixture paving, ny means mixing material rolling.)

| production process | Energy consumption(MJ) | Percentage of energy consumption (%) | Carbon emission (kg) | Percentage of carbon emissions (%) |
|--------------------|------------------------|--------------------------------------|----------------------|-------------------------------------|
| lqtt               | 1.16E+07               | 11.67                                | 8.46E+05             | 9.32                                |
| jldf              | 1.36E+06               | 1.37                                 | 9.35E+04             | 1.03                                |
| jlhg              | 4.79E+07               | 48.15                                | 3.91E+06             | 43.08                               |
| bhjd              | 2.14E+06               | 2.15                                 | 4.08E+05             | 4.5                                 |
| ys                | 2.75E+06               | 2.77                                 | 2.75E+06             | 30.36                               |
| tp                | 8.42E+05               | 0.85                                 | 8.43E+05             | 9.29                                |
| ny                | 3.04E+06               | 3.05                                 | 2.19E+05             | 2.42                                |
| total             | 9.96E+07               | 100                                  | 9.07E+06             | 100                                 |
4. Low carbon construction technology

4.1. Asphalt pavement temperature mixing technology

The use of Warm Mix Asphalt for paving can greatly reduce energy consumption and save costs. The principle of WMA is to use additives to reduce the viscosity of asphalt at high temperatures, so that the asphalt mixture can be mixed and constructed at relatively low temperatures. In general, WMA mixing, paving and rolling temperatures can be reduced by 20°C~50°C than the ordinary hot mix asphalt mixture. At present, there are dozens of kinds of products using warm mix additives on the market, which are mainly divided into four types: asphalt-mineral method, foamed asphalt warm mixing method, thixotropic organic additive, and emulsified asphalt-based warm mixing method. [16] The energy consumption reduced by warm mixing technology can be calculated by the formula.

$$EC = cm∆T$$  

Where EC: Reduced energy consumption (kJ); ∆T: Decrease temperature (°C); c: the specific heat capacity of the mixture (kJ/kg•K or kJ/kg•°C); m: Asphalt mixture quality (kg).

The energy saved is converted into heavy oil consumption, and the carbon emissions saved are calculated by the following formula.

$$m_h = \frac{EC}{40500}$$  

$$Q = m_h \times 3.07$$

Where Q: Reduced carbon emissions (kg); m_h: Mass of heavy oil consumed (kg).
The mixing temperature of the hot mix asphalt mixture is controlled at about 155 °C. If the initial temperature of the aggregate is 20 °C, the energy consumption per ton of hot mix asphalt mixture is 141700 kJ. The reduced energy consumption and carbon emissions per ton of warm mix asphalt mixture are shown in Table 10.

| Warm mix type                  | asphalt-mineral method | Sasobit | Foam asphalt | DAT |
|-------------------------------|------------------------|---------|--------------|-----|
| Lower temperature (°C)        | 10                     | 15      | 25           | 40  |
| Save energy (kJ)              | 10900                  | 16350   | 27250        | 43600 |
| Energy saving and emission reduction effect compared with HMA (%) | 7.7                     | 11.5    | 19.2         | 30.8 |
| Saving heavy oil (kg)         | 0.27                   | 0.40    | 0.67         | 1.08 |
| Reduce carbon emissions (kg)  | 0.83                   | 1.24    | 2.07         | 3.30 |

4.2. Control aggregate moisture content

The water content of the aggregate after drying shall not exceed 1%. If the water content of the aggregate is high, the heating temperature shall be increased. In the open-air environment, aggregates are inevitably affected by the environment, and rainwater is the biggest influencing factor\(^{[17]}\). During the heating and evaporation process, the temperature rise, vaporization and flue gas heating will increase the energy consumption. Building a shelter is the most effective measure to control the moisture content of the aggregate. After investigation, in the arid regions of Northwest China, the moisture content of open-air aggregates is more than 1.5% higher than that of shelters, and more than 2.5% higher in rainy areas in the east. After erecting the awning, the aggregate moisture content in the arid and rainy areas decreased by 1.5% and 2.5%, and the heavy oil consumption was reduced to 0.95kg/t and 1.58kg/t, and the energy consumption decreased by 37.85MJ/t and 60.52MJ/t. And the shelter can be recycled for repeated use. Therefore, the use of shelters to control the moisture content of aggregates is a cost-effective and cost-effective measure with low cost.

5. Conclusion

(1) The construction of asphalt surface layer will generate a lot of energy consumption. In order to achieve energy-saving and low-carbon construction, it is of great significance to establish a calculation model for energy consumption and carbon emissions. Based on the calculation theory of LCA, this paper determines the boundary conditions of asphalt surface layer energy consumption, which is divided into asphalt mixture production energy consumption, transportation energy consumption, paving energy consumption and rolling energy consumption.

(2) By investigating the energy consumption of asphalt pavement construction in many highways across the country, the benchmark parameters were obtained, and the energy consumption prediction formula of asphalt surface layer construction based on field measured data was established.

(3) The model is calculated using an example of an asphalt surface layer. Through the analysis of the calculation results, the three processes of mixture transportation, asphalt de-barrel heating, aggregate drying and heating are the key links of energy consumption and carbon emission in the whole asphalt surface layer construction process.

(4) Asphalt pavement warm mixing technology and building a shelter can effectively reduce energy consumption and carbon emissions during asphalt de-barrel heating and aggregate drying and heating, and have good energy-saving and emission-reducing effects.

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