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Original Research Paper

Evaluation system for CO_2 emission of hot asphalt mixture

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ABSTRACT

The highway construction industry plays an important role in economic and development, but is also a primary source of carbon emission. Accordingly, with the global climate change, energy conservation and reduction of carbon emissions have become critical issues in the highway construction industry. However, to date, a model for the highway construction industry has not been established. Hence, to implement a low-carbon construction model for highways, this study divided asphalt pavement construction into aggregate stacking, aggregate supply, and other stages, and compiled a list of energy consumption investigation. An appropriate calculation model of CO_2 emission was then built. Based on the carbon emission calculation model, the proportion of carbon emissions in each stage was analyzed. The analytic hierarchy process was used to establish the system of asphalt pavement construction with a judgment matrix, thereby enabling calculation of the weight coefficient of each link. In addition, the stages of aggregate heating, asphalt heating, and asphalt mixture mixing were defined as key stages of asphalt pavement construction. Carbon emissions at these stages accounted for approximately 90% of the total carbon emissions. Carbon emissions at each stage and their impact on the environment were quantified and compared. The energy saving construction schemes as well as the environmental and socioeconomic benefits were then proposed. Through these schemes, significant reductions in carbon emissions and costs can be achieved. The results indicate that carbon emissions reduce by 32.30% and 35.93%, whereas costs reduce by 18.58% and 6.03%. The proposed energy-saving and emission reduction scheme can provide a theoretical basis and technical support for the development of low-carbon highway construction.

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1. Introduction

The greenhouse effect has a serious impact on the national system and social economy. The traffic industry is an important source of greenhouse gas and air pollution emissions. Hence, It has become one of the key industries in the development of alternation for low-carbon emissions, as explicitly proposed by Ministry of Environmental Protection to speed up highway construction. Generally, traditional hot mix asphalt is used in pavement construction, which emits large quantities of CO_2, CH_4, and N_2O (Deng and Cheng, 2002; Wang et al., 2003; Yan, 2011). This material is part of the high-carbon emission model, and is considered as an element of the carbon emissions disaster area of the highway industry, which is unfavorable to the development of a low-carbon economy. The International Energy Agency (IEA) reported that CO_2 emissions from the transport industry account for approximately 25% of global emissions (IEA, 2009). Pollutants and greenhouse gas emissions from transport accounted for 8% of the total emission in China (Cai et al., 2001), a country that also has large energy consumption. Hence, efforts are currently focused on building mechanisms for the energy-saving emission reduction. Annually, approximately 350 million tons of raw materials are used in the construction and maintenance of national highways annually (Nicholas, 2009) and roughly 7×10^6 MJ energy is required to build a 1 km standard two-lane asphalt road (Lee et al., 2010). In Denmark, the transport sector generates CO_2 emissions that account for approximately one third of the total CO_2 emissions of domestic industries, with approximately 95% of the emissions directly caused by traffic infrastructure construction and operation (Schmidt and Dyre, 2012).

Numerous studies on the influence of carbon emissions from the highway transport industry have been conducted by scholars both locally and abroad. Cass and Mukherjee (2010) analyzed and compared the design of pavement materials based on emission inventories, and provided a calculation method based on the process of carbon emissions, with a concrete pavement reconstruction project to illustrate the method. After establishing a calculation model of carbon emissions with the application of life cycle analysis method, Pan (2011) integrated energy consumption and emission inventory. The study also introduced energy-saving and emission reduction measures for highways. However, the models found in domestic and international researches on the study of carbon emissions mainly focused on building life cycle carbon emissions. Studies on the environmental pollution caused by asphalt pavement construction have not

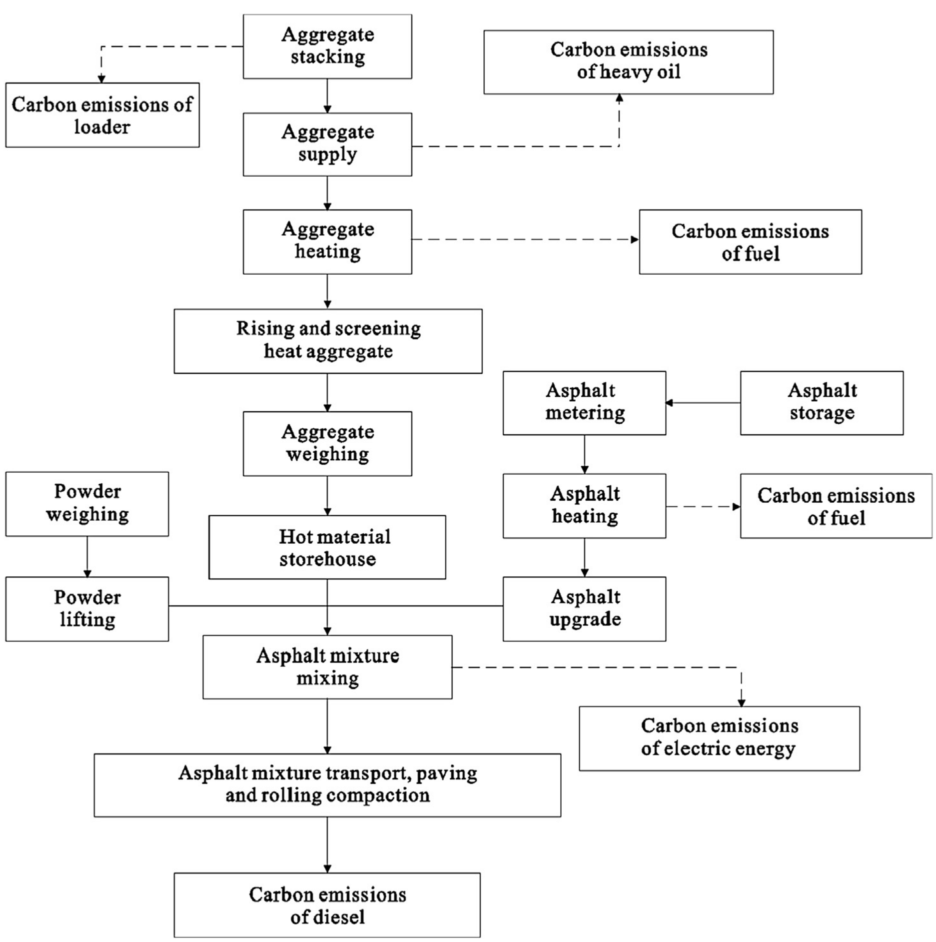

Fig. 1 – Production and construction process of asphalt mixture.

yet been thoroughly conducted. Moreover, research on the carbon emissions evaluation and energy-saving measures only start recently, and its pertinence is weak.

In this study, the calculation model of carbon emission and the analysis on the key stages and influencing factors of carbon emissions were established based on the analysis on energy consumption in asphalt mixture production and construction. This approach would provide a theoretical support for the development of low-carbon technology for asphalt pavement construction and the selection of low-carbon technology.

2. Investigation of asphalt mixture carbon source

2.1. *Definition of carbon emission stage*

A highway is a product that can comprehensively evaluate the entire construction process from its input or output of energy and carbon emissions. Carbon sources or carbon emission sources are formed in the pavement structure within the boundary of the pavement system, including a series of intermediate products and the unit process of collection. Through data acquisition, the degree of influence and the system boundaries can be reasonably identified.

Asphalt pavement construction was divided into two parts, namely, asphalt mixture production and asphalt mixture construction. Asphalt mixture production includes aggregate stacking, aggregate supply, asphalt heating, aggregate heating, and mixture mixing. The construction of asphalt mixture was divided into asphalt mixture transportation, asphalt mixture paving, and compaction of asphalt mixture. Based on the carbon source investigation in these stages, statistics and calculation of asphalt mixture carbon emissions were conducted.

2.2. *Carbon source investigation*

With a good pavement performance and a capacity satisfying the requirements of various pavement structure layers, hot mix asphalt has been widely used in China. Through the highway boundary definition, a detailed investigation of asphalt pavement construction was conducted and the energy consumption of each stage was obtained, which laid a foundation for the calculation model and the determination of the key stages. The production, construction, and carbon flow are shown in Fig. 1.

(1) Aggregate stacking

Aggregate is transported and piled by a loader at a specific location in the mixing station. The main energy source consumed during this process is diesel oil. Therefore, the main content of the investigation is the energy consumption unit mass of aggregate during this process by loading machine.

(2) Aggregate supply

In the thinning process, the aggregate is transferred to a cold aggregate bin by the loader. The main energy source consumed is fuel oil of the loader. Hence, to investigate fuel consumption, the production power of the asphalt mixing station with the loader collocation is considered, and the inclusion of each type of loader is specified in the questionnaire. The main targets of the investigation are the workload and fuel consumption of different types of machines per unit time.

(3) Aggregate heating

The aggregate conveyed from a material field has a specific water content, which requires a drying step. Asphalt mixture is mixed under a high temperature and thus the aggregate needs to be heated to a high temperature (generally 160 °C–190 °C). Drying and heating the aggregates are achieved by using a drying drum. The main energy consumptions are heavy oil and natural gas. Thus, the main parameters investigated are the consumption of energy per unit time, matching amount of production per unit time, and asphalt mixing station power.

(4) Asphalt supply

Before being transferred to a mixing pot, the asphalt binder must be heated in an asphalt storage tank to reach the correct temperature while maintaining a sufficiently low viscosity. Thus, mixing the asphalt binder with a dried aggregate is good. Heating the asphalt binder is achieved mainly through a thermal heating fluid, with heating temperature generally between 150 °C and 170 °C. Hence, the main content of the research in this phase is the energy consumption per unit time.

(5) Asphalt mixture mixing

Asphalt mixture mixing mainly includes aggregate lifting by material hoist, vibrating screen for screening, aggregate weighing, blending and other processes. In these processes, electrical energy is the major consumption, which is related to the power of asphalt mixing stations. Therefore, the main parameter in this stage is electrical energy consumption per unit time corresponding to the produced power.

(6) Asphalt mixture transport

The mixed asphalt mixture should initially be transported from the mixing site to the paving site by the transport vehicle, all of which involve consumption of diesel. Hence, in this stage, transport vehicle load and corresponding fuel consumption are investigated.

(7) Asphalt mixture paving

The use of a paver is dependent on the width, thickness, cross slope and longitudinal slope. This type of machinery consumes large amounts of fuel. Hence, unit time consumption and spreading amount of the paver are investigated in this stage.

(8) Asphalt mixture rolling compaction

Asphalt pavement rolling is an effective method of improving the comprehensive performance of asphalt pavement. In this process, diesel oil is the main energy source. The main contents of the survey are roller fuel consumption per unit time and unit time workload.

The entire production and construction stage of asphalt mixture is an interrelated process. The production condition of each stage should match the capacity of the asphalt mixing plant and serve as a starting point to investigate energy consumption through either a direct or indirect method. Results provide support for the establishment of asphalt mixture of carbon emissions.

Table 1 – Investigation of asphalt mixture energy consumption.

Expressway	Aggregate stacking (diesel) (L/t)	Asphalt heating	Aggregate supply (diesel) (L/t)	Aggregate heating	Transportation (diesel) (L/km·t)	Mixture mixing (electricity) (kWh/t)	Mixture paving (diesel) (L/t)	Mixture rolling (diesel) (L/t)
Shaanxi Province A	0.149	64.502 (coal) (kg/t)	0.086	7.614 (oil) (kg/t)	0.030	2.33	0.133	0.267
Yunnan Province B	0.158	68.423 (coal) (kg/t)	0.122	6.680 (oil) (kg/t)	0.060	5.36	0.257	0.407
Gansu Province C	0.164	35.124 (oil) (kg/t)	0.068	7.054 (oil) (kg/t)	0.012	3.95	0.221	0.321
Gansu Province D	0.177	34.928 (oil) (kg/t)	0.128	7.084 (oil) (kg/t)	0.009	2.83	0.210	0.287
Shaanxi Province E	0.134	34.207 (oil) (kg/t)	0.090	6.729 (oil) (kg/t)	0.008	2.21	0.128	0.226
Shaanxi Province F	0.145	34.961 (oil) (kg/t)	0.080	7.301 (oil) (kg/t)	0.008	2.50	0.136	0.221
Shaanxi Province G	0.139	33.542 (gas) (m^3/t)	0.156	7.113 (gas) (m^3/t)	0.011	2.63	0.107	0.187
Shaanxi Province H	0.166	34.525 (gas) (m^3/t)	0.112	7.359 (gas) (m^3/t)	0.013	3.15	0.144	0.337
Shaanxi Province I	0.150	36.521 (gas) (m^3/t)	0.121	7.599 (gas) (m^3/t)	0.010	3.00	0.213	0.280
Shaanxi Province J	0.162	32.530 (gas) (m^3/t)	0.112	8.135 (gas) (m^3/t)	0.010	2.81	0.190	0.300

2.3. *Investigation of asphalt mixture carbon emission*

The expressways in Shaanxi, Yunnan, Gansu, Hunan and other provinces were elected to investigate the carbon emissions of expressways. The type and amount of energy consumed at various stages of highway construction were investigated. In addition, statistical analysis of energy consumption in different stages of highway construction was also carried out. Table 1 shows the survey results of energy consumptions of expressways in China.

3. Calculation of asphalt mixture carbon emission

3.1. *Establishment of calculation model*

Asphalt production and construction contain various stages with different energy consumptions in each stage. The energy will also produce different types of greenhouse gases. The first step of the calculation model is to determine the measured parameters. Carbon emission factors (Deng et al., 1999; Hanson et al., 2011; IPCC, 1996; Shang et al., 2010; Wang and Li, 2005; Zhuang, 2011) provided by Intergovernmental Panel on Climate Change (IPCC) were used to calculate the carbon emissions of various energy consumptions. The global and representative carbon emission factors proposed according to the global climate change are suitable for Chinese carbon emissions calculation of expressway. They are shown in Table 2.

In the basis of carbon emission factors, the different greenhouse gases, according to the global warming potential (G_{wp}) (Bernstein et al., 2008; Gschosser and Wallbaum, 2012), were transformed into CO_2 equivalents (IPCC, 2006; Pan and Wang, 2011). Then, carbon emissions were calculated and compared using CO_2 equivalents. The G_{wp} is shown in Table 3.

For better statistics, various aspects of carbon emissions were compared in line with the intuitive needs of the selected measurement parameters. The carbon emissions produced by production and construction of 1 t asphalt mixture were elected to be comparative objects. It can objectively reduce the mutual influence of each link and enhance the accuracy of data. In this paper, CO_2 and CO_2 transformed from other greenhouse gases with the G_{wp} were considered as carbon emissions in this paper.

Each kind of greenhouse gas was converted into their CO_2 equivalent according to the G_{wp}, and the calculation of all greenhouse gases was summarized. The equivalent total emission can be calculated based on the previous calculation. Combined with the production of asphalt mixture and each stage of construction, the quantification model of carbon emission was determined ultimately. The quantification model is as follow

$$G = \sum_i \sum_j \sum_k m_{ij} Q_j P_j G_{wpk}$$

where G is the total carbon emissions, m_{ij} is energy j consumption in stage i, Q_j is the unit heat quantity of energy j, P_j is

Table 2 – Carbon emission factor according to energy type.

Energy type		Coal	Fuel oil	Diesel/petrol	Asphalt	Natural gas
Default value for emission factor (mg/MJ)	CO_2	94,600	77,400	74,100	80,700	56,100
	CH_4	1	3	3	3	1
	N_2O	1.5	0.6	0.6	0.6	0.1

the carbon emission factors of energy j, G_{wpk} is the G_{wp} of the greenhouse gas k.

3.2. *Investigation on expressway carbon emission*

According to the investigation on Chinese expressways and the calculation model, the carbon emissions at each stage of the road asphalt mixture production and construction were calculated, and the carbon emissions of each expressway were obtained (Fig. 2).

According to the calculation results, the carbon emissions from asphalt mixture production and construction have significant differences. The total carbon emission is similar to the energy of various sector types. When the energy types differ, the total carbon emissions have large differences. The main reason behind this phenomenon is that the production and construction of asphalt mixture are complicated processes. Carbon emissions are not only related to the construction technology, machinery, and construction team on service life, but also to the type of fuel, construction management, and other aspects. Carbon emissions can reduce considerably when clean energy sources are selected as fuel. The reduction of aggregate moisture can contribute to a reduction in carbon emissions in the construction process.

4. Analysis on carbon emission

Given that the production and construction of asphalt mixture involve several processes, each process requires a specific device, consumes various types of energy, and has great difference in the carbon emissions quantity. Through the analysis on different processes of carbon emissions, the key stages of carbon emissions were defined and a theoretical support was provided to develop a low-carbon emission reduction technology and a reasonable scheme to control carbon emissions.

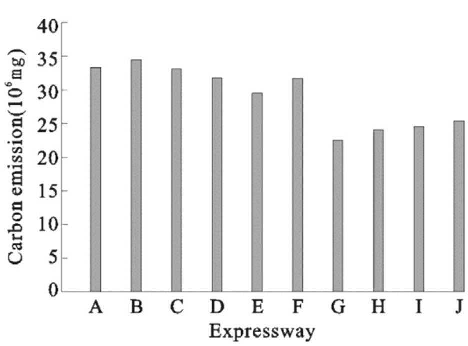

Fig. 2 – Expressway carbon emissions.

Table 3 – Global warming potential.

Greenhouse gas type	CO_2	CH_4	N_2O
CO_2 equivalent	1	21	310

4.1. *Analysis on proportion of carbon emission*

The production and construction processes of asphalt mixture included asphalt heating in a barrel, aggregate heating, and so on. Energy consumed in the eight stages varied. According to different energies consumed in different stages, the 10 expressways were divided into three classes, namely, A, B and C. A denotes the asphalt heating process with coal and aggregate heating process with heavy oil. B is for asphalt heating and aggregate heating process with heavy oil. C stands for asphalt heating and aggregate heating process with natural gas. Based on the calculation model and the comparison of carbon emissions in each stage, the proportions of carbon emissions were obtained and the average value of each type was taken as representatives (Table 4).

The above analysis shows that the energy types were different, but each stage has a similar proportion of carbon emissions. Aggregate heating accounted for the largest proportion of carbon emissions, approximately 67% of the total carbon emissions. Asphalt heating accounted for approximately 14% of the total carbon emissions, while mixture mixing accounted for approximately 11% of the total carbon emissions. Consequently, aggregate heating, asphalt heating, and mixture mixing together accounted for more than 90% of carbon emissions in the whole carbon emission process, thus these processes had the biggest impact on carbon emissions. The rest of the stages had a slight influence on total carbon emission.

4.2. *Weight calculation of carbon emission*

Based on the calculation and comparison of carbon emissions in every stage of production and construction of asphalt mixture, this paper identified the situation of carbon

Table 4 – Proportion of carbon emission in each stage.

Stage	A (%)	B (%)	C (%)
Aggregate stocking	1.14	1.23	1.63
Aggregate supply	0.84	0.77	1.37
Aggregate heating	65.39	69.00	65.36
Asphalt heating	15.24	14.93	13.00
Mixture mixing	12.87	10.33	13.67
Mixture transport	0.14	0.78	0.12
Mixture paving	1.52	1.46	1.80
Mixture rolling	2.63	2.21	3.04

emissions in each stage and provided the corresponding weights (Mai et al., 2007; Saaty, 1980). Through the analysis on weight function, the key stages in the whole carbon emission process could be intuitively determined, thus reducing the impact caused by information bias or lack of comparison. In this paper, the weights of each stage in the asphalt mixture production were calculated by the analytic hierarchy process (Huang et al., 2010). The specific steps are as follows.

Step 1: Establish a hierarchical structure system. The system was divided into eight stages, namely, aggregate stocking carbon emissions, aggregate supply carbon emissions, aggregate heating carbon emissions, asphalt heating carbon emissions, carbon emissions of mixture mixing process, mixture transport carbon emissions, mixture paving carbon emissions and mixture material rolling carbon emissions.

Step 2: Based on the proportion of carbon emissions and the importance of scale (Table 5), pairwise comparisons were conducted the importance of element compositions to define the impact of each stage and establish an 8 × 8 matrix.

Judgment matrix:

$$a_{8\times8} = \begin{bmatrix} 1 & 2 & 1/8 & 1/7 & 1/6 & 4 & 1 & 1/3 \\ 1/2 & 1 & 1/8 & 1/7 & 1/6 & 4 & 1/2 & 1/4 \\ 8 & 8 & 1 & 4 & 5 & 9 & 8 & 7 \\ 7 & 7 & 1/4 & 1 & 3 & 8 & 7 & 5 \\ 6 & 6 & 1/5 & 1/3 & 1 & 7 & 5 & 4 \\ 1/4 & 1/4 & 1/9 & 1/8 & 1/7 & 1 & 1/4 & 1/5 \\ 1 & 2 & 1/8 & 1/7 & 1/5 & 4 & 1 & 1/3 \\ 3 & 4 & 1/7 & 1/5 & 1/4 & 5 & 3 & 1 \end{bmatrix}$$

Step 3: Largest eigenvalue and eigenvectors of matrixes.

The largest eigenvalue of matrixes can be calculated by Microsoft Excel. $\lambda_{max} = 8.8665$, $\omega_i = (0.0416, 0.0324, 0.4410, 0.2494, 0.1625, 0.0189, 0.0422, 0.0798)$.

The consistency test of the largest eigenvalue of matrices was conducted:

$$CI = (\lambda_{max} - n)/(n-1) = (8.8665 - 8)/(8-1) = 0.1238$$

$$CR = CI/RI = 0.1238/1.41 = 0.088 \leq 0.10$$

Thus, the target matrix had satisfactory consistency and had satisfied the requirements of the analytic hierarchy process. The results were credible.

Table 5 – Importance of scale.

Scale a_{ij}	Definition
1	Factor *i* is equally important to factor *j*
3	Factor *i* is slightly more important than factor *j*
5	Factor *i* is more important than factor *j*
7	Factor *i* is much more important than factor *j*
9	Factor *i* is absolutely more important than factor *j*
2, 4, 6, 8	Intermediate values between the adjacent factors
Reciprocal	Importance of *j* compared with *i* is the reciprocal of a_{ij}

Step 4: The weight coefficient of carbon emissions in each stage was calculated based on the eigenvalue, as shown in Table 6.

The weight function directly reflected the relative degree of influence of each stage. From Table 6, the weight of the aggregate heating stage was the largest at 0.4130, followed by the weight of asphalt heating at 0.2335 and then by mixture mixing at 0.1522. The weights of the other stages were small and had a small effect on carbon emissions. The carbon emissions in aggregate heating, asphalt heating, and mixture mixing processes accounted for a large proportion of the total carbon emissions.

4.3. *Analysis on carbon emissions in key stages*

Based on the above analysis, the energy types were different but had similar proportions of carbon emissions in each stage. The carbon emissions in aggregate heating, asphalt heating, and mixture mixing together accounted more than 90% of the total amount of carbon emissions. Aggregate heating accounted for approximately 67%, asphalt heating without barrel accounted for 14%, mixture mixing approximately 11%, and the other stages occupied less than 10%.

According to the analysis on the weight function, the weights of aggregate heating, asphalt heating without barrel, and mixing stages were 0.4130, 0.2335, and 0.1522, respectively, accounting for a large proportion (0.8) of the sum of the total weight (1.0). Thus, the total weight of the other stages was quite small (0.2). The stages that owned the majority of the weight had a dominant influence on the carbon emission.

According to the analysis on the proportion of carbon emissions and weight function, given the different types of energy, more than 80% of the carbon emissions were produced in the aggregate heating, asphalt heating, and mixture mixing stages, which were the major sources of carbon emissions in the production and construction of asphalt mixture. Accordingly, aggregate heating, asphalt heating, and mixture mixing were defined as the key stages of carbon emissions of asphalt mixture. Analysis on the key stages of carbon emissions played an important part in the study on carbon emissions in the whole process.

5. Carbon emission evaluation

The production and construction of asphalt mixture from raw material to completed asphalt pavement completion include various construction processes. Each construction process

Table 6 – Weight of carbon emissions in each stage.

Stage	Weight
Aggregate stacking	0.0389
Aggregate supply	0.0304
Aggregate heating	0.4130
Asphalt heating	0.2335
Mixture mixing	0.1522
Mixture transport	0.0177
Mixture paving	0.0395
Mixture rolling	0.0748

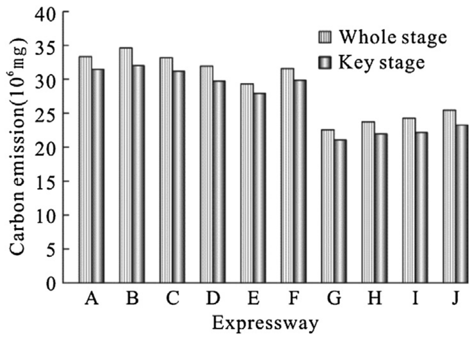

Fig. 3 – Carbon emissions in whole stage and key stage.

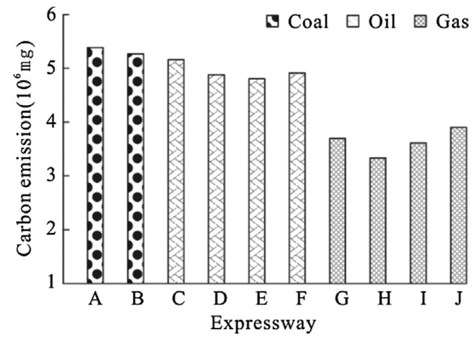

Fig. 5 – Carbon emissions of asphalt heating.

consumes a large amount and different types of energy. The carbon emissions of the whole stages and the key stages were obtained, and the relationship between total carbon emissions and carbon emissions from the key stages is shown in Fig. 3.

Fig. 3 shows that given the similar trend between total carbon emissions and carbon emissions in the key stages, the evaluation on carbon emissions of construction and production of asphalt mixture could be obtained by evaluating the carbon emissions of key stages. Considering that the primary energy in mixture mixing is industrial electricity, which has less greenhouse gas emissions and stable energy consumption, this type of electricity had a small impact on total carbon emissions. Therefore, the evaluation of key stages only depends on aggregate heating and asphalt heating.

Fig. 4 shows that carbon emissions in the aggregate heating stage using natural gas was lower than that using heavy oil. Natural gas with clean combustion, high calorific value, and high combustion efficiency released less carbon emissions after combustion. Heavy oil can achieve atomization combustion (Cao et al., 2003) but with incomplete combustion. Thus, heavy oil releases more carbon emissions than natural gas to generate the same quantity of heat.

Fig. 5 shows the carbon emissions from asphalt heating without barrel. In the stage of asphalt heating, carbon emissions from using natural gas reached the minimum, followed by using heavy oil. Carbon emissions from using coal also reached the maximum. Coal, as the main fossil fuel, has low heat value and low combustion efficiency. To generate the same amount of heat, the amount of coal needed is about 1.34 times the quality of diesel or 2.04 times of natural gas. The calorific value of coal is unstable with strong equipment dependence.

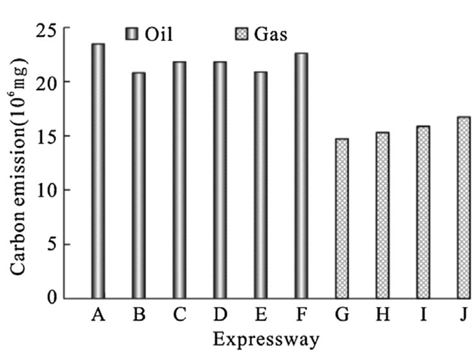

Fig. 4 – Carbon emissions of aggregate heating.

In the comparison between carbon emissions in the key stages, carbon emissions by using natural gas emitted the least carbon. Natural gas was found to be the best energy choice for the production and construction of asphalt mixture. Heavy oil for heating was the second least in carbon emissions. If natural gas is unavailable, then using heavy oil is appropriate for heating. In the condition where natural gas and heavy oil are unavailable, the coal can be used as fuel for heating.

6. Analysis on emission reduction effect and economic benefits

6.1. *Analysis on change of energy type*

The analysis on energy saving and emission reduction in the key stages was based on the carbon emission evaluation. According to the market price, coal was 500 RMB/t, heavy oil was 4500 RMB/t, and natural gas was 3.41 RMB/m^3. A ton of asphalt mixture was used as the unit of measurement. The emission reduction effect is shown in Table 7.

The main energy sources are heavy oil and natural gas at the aggregate heating stage. In this stage, the carbon emissions and cost would reduce by 27.72% and 18.63% when natural gas replaced heavy oil. In the asphalt heating stage, there were three ways accepted to reduce the carbon emissions, namely, coal to heavy oil, coal to natural gas and oil to natural gas. Because the cost of coal was significantly lower than the heavy oil, the carbon emissions can reduce 18.34% when oil took the place of coal, but the cost would increase 4.58 RMB. The carbon emissions and cost can reduce by 27.53% and 1.09 RMB respectively, and the effect of energy saving and emission reduction was remarkable when natural gas was elected rather than heavy oil. The carbon emissions reduced by 40.82%, and the cost increased 3.49 RMB, but the reduction effect was best when natural gas replaced coal.

The analysis on the emission reduction effect showed that the use of natural gas yield the minimum carbon emissions and relatively lower cost. With heavy oil as energy, the carbon emission and cost slightly increase. Emission reduction effect of coal the worst with the highest carbon emissions.

Table 7 – Reduction effect of carbon emissions in key stages.

Stage	Measure	Reduction (mg)	Reduction rate (%)	Cost change (RMB)	Cost change rate (%)
Aggregate heating	Oil to gas	6,110,600	−27.72	−5.69	−18.63
Asphalt heating	Coal to oil	955,180	−18.34	4.58	350.00
	Oil to gas	1,171,197	−27.53	−1.09	−18.49
	Coal to gas	2,126,377	−40.82	3.49	267.00

6.2. Analysis on the effects of energy saving and emission reduction with reduced water content

Aggregate heating is the key stage in the production and construction of asphalt mixture. This stage is essential to understand the relation between water content and carbon emissions in order to reduce carbon emissions.

With heavy oil as an example, the energy consumption was recorded when the moisture content was reduced. The carbon emissions were calculated and the cost was obtained according to the market research. In the condition where asphalt aggregate ratio was 5.1%, powder content was 4%, mixing plant production capacity was 300 t/h, aggregate heating temperature was 175 °C, when the moisture content reduced by 1%, the changes in energy consumption and cost could be calculated by the quantity of aggregate required to produce 1 t of asphalt for units of measurement. The energy saving effect is shown in Table 8.

From Table 8, the water content of the aggregate asphalt mixture had an important role in reducing carbon emissions. Reducing the moisture content can save energy and reduce carbon emissions in aggregate heating. Taking effective measures such as building a canopy to reduce water content is an effective way to reduce carbon emissions.

7. Energy saving and emission reduction construction scheme

7.1. Energy saving and emission reduction in key stages

An energy saving and emission reduction construction scheme in key stages was proposed according to the analysis on energy saving and emission reduction effect. The consumption of energy and carbon emissions in the production and construction of asphalt mixture could reduce by controlling the energy saving and emission reduction in key stages.

According to the survey, the price of a material storage in the market is 120 RMB/m^2, the storage area is approximately 3000 m^2, and the cost of building a storage shed is nearly 360,000 RMB. After building the material storage shed, the moisture content decreased from 3% to 2%, and the gas saved would be approximately 0.61 m^3 according to the test. For example, to build an asphalt pavement which is 10 m wide, 18 cm thick, and has an asphalt aggregate ratio 4.8%, the saving in construction of a 3.1 km asphalt pavement would make up for the cost of a canopy. In addition, the material storage shed can be reused in the follow-up project. One ton of asphalt mixture was considered as an objective comparison object. The energy saving and emission reduction scheme is shown in Table 9.

In the asphalt heating stage, although the cost increased when the coal was replaced by natural gas, natural gas had the best emission reduction effect. Generally, changing the energy type and building a canopy and other measures not only reduced carbon emissions, but also effectively reduced the cost.

7.2. New heating technology

With the development of high technology, green and environmentally friendly heating technologies have been proposed such as infrared radiation heating, high-temperature superconducting pipe heating (Li and Deng , 2010), solar heating in key stages. These new technologies provide new directions for a future development that will radically reduce carbon emissions brought in to produce and construct asphalt pavement. In the near future, mature and practical technologies or processes will be the new direction for energy development in the highway construction industry.

8. Conclusions

Asphalt pavement construction was divided into two parts, namely, asphalt mixture production and asphalt mixture construction, based on the analysis on the asphalt mixture production and construction process. Asphalt mixture production included aggregate stacking, aggregate supply, asphalt heating, asphalt mixing and so on. Asphalt mixture construction included asphalt mixture paving, transport, rolling and other stages.

By analyzing the investigation of carbon sources, this paper puts forward 1 t of asphalt mixture as a horizontal comparison object. The carbon emission calculation model is determined using the analytic hierarchy process, and then the weight coefficient of each stage is calculated.

Analyzing the ratio of carbon emissions and the weight coefficients of different stages helped to determine the key

Table 8 – Energy saving, emission reduction, and cost change in aggregate heating.

Moisture reduction rate (%)	Energy-saving rate (%)	Emission reduction rate (%)	Cost change rate (%)
1.00	9.17	8.92	9.30

Table 9 – Energy saving and emission reduction construction scheme.

Stage	Measure	Energy saving (MJ)	Emission reduction (mg)	Emission reduction rate (%)	Cost change (RMB)	Cost change rate (%)
Aggregate heating	Oil to gas	33.95	6,110,600	27.70	−5.69	−18.63
	Building canopy	20.63	1,224,190	5.60	–	–
Asphalt heating	Oil to gas	6.59	1,171,197	27.50	−1.09	−18.49
	Coal to gas	10.96	2,126,377	40.82	3.49	267.00
Total (oil to gas)		61.17	8,505,987	32.30	−6.78	−18.58
Total (coal to gas)		65.54	9,461,167	35.93	−2.20	−6.03

stages of carbon emissions, namely, heating aggregates, asphalt heating, and mixing process, which accounted for 67%, 14%, and 12% of total carbon emissions respectively.

Based on quantification comparative analysis on carbon emissions of asphalt mixture, combined with the proportion relationship between carbon emissions in key stages and total carbon emissions in asphalt production and construction, a comprehensive evaluation was made on the carbon emissions of asphalt mixture.

Based on the analysis of carbon emission evaluation and economic benefit, a corresponding energy saving construction program was proposed to save on the cost of asphalt mixture production and construction, as well as to reduce fuel consumption and carbon emissions.

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