Research Article

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Carbon emissions analysis of producing modified asphalt with natural asphalt

https://doi.org/10.1515/gps-2022-8146
received December 05, 2022; accepted April 24, 2023

Abstract: The modification mechanism of modified asphalt with natural asphalt was analyzed through Fourier transform infrared spectrum. The results show that the modification mechanism of both the natural asphalt and petroleum asphalt is mainly a physical blending process. The polar functional groups contained in natural asphalt make modified asphalt with natural asphalt have characteristic good scaling resistance and water stability. Subsequently, the carbon emissions of each link of asphalt production stage were quantified, and the influence of mining, transportation, and processing on the total carbon emissions were all analyzed by establishing the carbon emission calculation model of asphalt production. The calculation results of GREET model showed that the equivalent carbon dioxide emission (CO_2e) of rock asphalt mining was only 9.4% of that of crude oil production. At the same time, the CO_2e of modified asphalt with natural asphalt processing was 44.7% lower than that of petroleum asphalt, and the carbon emission of rock asphalt transportation accounted for only 1/3 of that of petroleum asphalt transportation. Furthermore, the increased energy consumption caused by petroleum asphalt transportation and modified asphalt with natural asphalt processing will partially offset the contribution of natural asphalt to reducing carbon emissions. Meanwhile, the CO_2e of modified asphalt with natural asphalt was lower than that of petroleum asphalt when the content of natural asphalt exceeded 18%. Thereafter, the analytic hierarchy process calculation results showed that petroleum asphalt processing and transportation had the largest weight of carbon emissions in the production stage of modified asphalt with natural asphalt. Ultimately, it is significant to further reduce carbon emissions by increasing the content of natural asphalt, which will then inevitably lead to the reduction in the production and transportation energy consumption of petroleum asphalt.

Keywords: quantification of carbon emissions, GREET model, modified asphalt with natural asphalt, analytic hierarchy process, carbon emission weight

1 Introduction

The energy consumption for road construction is huge due to the rapid development of the road traffic industry, and the resulting greenhouse effect seriously affects the environment, manufacturing, and daily life of people as a whole [1–3]. According to statistics, asphalt pavement roads make up about 90% of all roads paved in Europe, with that number being 94% in the United States, 90% in Canada, and 96% in Mexico [4]. The total mileage of roads in China has exceeded 5 million kilometers, including more than 1 million kilometers of asphalt pavement by the end of 2020, and moreover, more than 90% of new roads are asphalt pavements [5,6]. Thus, if a positive outlook is to be adopted, it becomes urgent to immediately start to control and reduce greenhouse gas emissions as much as possible in the process of asphalt production and use, by strictly controlling and regulating energy consumption and greenhouse gas pollution as much as possible.

Low-carbon technologies for pavement construction have attracted more and more attention in a bid to achieve the goal of carbon reduction. Yang [7] proposed a construction technology of low carbon and thin paving for in-place thermal regeneration of high-grade asphalt pavement. The energy-saving effect and cost of warm mixing technology was calculated and analyzed, and the key indicators of low energy consumption and low carbon construction technology for asphalt pavement were proposed by Hu [8]. Peng et al. [9] proposed two types of low-carbon technologies, natural gas was used to reduce energy consumption and improve energy utilization on the energy consumption side, while low-carbon

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asphalt mixture with warm mixing technology was used to reduce carbon emissions from mixture volatilization. Thives and Ghisi [10] explained that warm mixing technology can save 20–70% of energy consumption of hot mix asphalt. Wang et al. [11] proved that the emission reduction capacity of asphalt rubber is stronger than that of SBS-modified asphalt. Hu and Sun [12] calculated quantitatively that the emulsified asphalt cold in-plant recycling technology can save energy by 35.3% and reduce carbon emissions by 10.71%.

To sum up, the technology of low-carbon emission reduction is mainly divided into two aspects, material production and material use. In terms of material production, the asphalt products with low energy consumption, such as emulsified asphalt, asphalt rubber, etc., are mainly adopted. In terms of material use, the warm mixing technology, producing, and paving low-carbon asphalt mixture through additives that can reduce the temperature, or the pavement recycling technology, is mainly used. Compared with the warm mixing technology with high cost and the pavement recycling technology with complex processes, it is undoubtedly an economic and environmentally friendly alternative to directly control carbon emissions from the asphalt production process by adopting cost-effective raw materials. However, emulsified asphalt has insufficient performance, and rubber modified asphalt produces too much smoke and dangerous gases. As the original and natural form of petroleum asphalt, natural asphalt contains invaluable inorganic substances, namely, calcium carbonate, and other heavy components. The average particle size of inorganic substances in natural asphalt are ground to about 5 μm when producing modified asphalt with natural asphalt in order to fully release the effective ingredients in the natural asphalt. This can help to significantly improve the performance of asphalt, thus helping build low-carbon green ecological roads. Natural asphalt is a natural pitch, which belongs to raphaelite with petroleum asphalt. It can be used directly after mining without having to go through the refining process of crude oil, and it can be transported in bulk at room temperature. The carbon emission in the production of modified asphalt with natural asphalt is lower than that of petroleum asphalt, which is a high-quality material for building a low-carbon green ecological road. The application of natural asphalt can greatly improve pavements' overall performance, including the high-temperature stability and moisture damage resistance of pavements [13,14]. The micronized modified asphalt with natural asphalt is obtained by the grinding process. It also includes other processes after mixing natural asphalt and petroleum asphalt according to different proportions, resulting in a kind of finished modified asphalt with natural asphalt material.

Life cycle assessment (LCA) is an international standard for systematically and quantitatively describing various energy consumption and environmental emissions in the life cycle of a product, and to evaluate their environmental impact. The construction of asphalt pavement is complex and complicated, it thus becomes necessary to divide asphalt pavement construction into raw material production stage, transportation stage, and construction stage to calculate energy consumption generated in different links of each stage, respectively [15,16]. Carbon emission in the transportation and construction stage was mainly calculated in previous studies. It is thus necessary to study the production stage of natural asphalt raw materials based on LCA method.

Carbon emission of petroleum asphalt and modified asphalt with natural asphalt was evaluated quantitatively, and the impact of natural asphalt content on the carbon emission and the carbon emission of each production link of modified asphalt was analyzed by establishing a carbon emission calculation model in the asphalt production stage. The carbon emission weight of each link of modified asphalt with natural asphalt production stage was studied based on the analytic hierarchy process (AHP) calculation, which then provided the basis for energy conservation and emission reduction.

2 Raw materials

2.1 Qingchuan rock asphalt (QRA)

The technical parameters and four-component results of QRA are shown in Table 1. Also, the Fourier transform infrared spectrum (FTIR) of Qilu 70# and QRA are shown in Figure 2.

According to the results of the four-components in Table 1, the asphaltene and resin in QRA accounts for 98% of the total composition, especially the asphaltene which made up a whopping 86.1%. Asphaltene and resin are macromolecular components that can reduce the temperature sensitivity of asphalt. According to the FTIR in Figure 1, it can be deduced that the bitumen in QRA is basically the same as that in petroleum asphalt at the chemical group. Therefore, QRA and petroleum asphalt can fuse well, and it is not easy to encounter segregation and degradation which are prominent in other polymer

Table 1: Technical indicators of QRA

Items		QRA	Test method
Shape		Black brown powder	Visualization
Ash content (%)		21.1	T 0614
0.15 mm mesh passing rate (%)		96.4	T 0327
0.075 mm 0.15 mm mesh passing rate (%)		92.1	T 0327
Four fractions of asphalt (%)	Saturated fraction	0.1	T 0618
	Aromatic fraction	1.9	
	Resin	11.9	
	Asphaltene	86.1	

modifiers. The polar functional groups in QRA are mainly distributed in asphaltene and resin. The adsorption between them and aggregate is polar adsorption and chemical adsorption, which can greatly improve the adhesion between asphalt and aggregate and improve the water resistance. In addition, QRA contains minerals such as silicate, $CaCO_3$, $CaSO_4$, and a small amount of Fe_2O_3 and Al_2O_3, which are metal oxides, plus the existing Si–O or C–O also belong to polar functional groups.

2.2 Modified asphalt with natural asphalt

Modified asphalt with natural asphalt was prepared by the micronized process with QRA percentages of 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, and 25%, respectively. The penetration, softening point, and viscosity of the modified asphalt with different QRA contents were tested, and the test results are shown in Table 2. The particle size of inorganic substances in modified asphalt with natural asphalt was tested using a laser particle size analyzer. The particle size distribution is shown in Figure 2.

As can be seen from Table 2, with the QRA content increase, the penetration of modified asphalt with natural asphalt decreases, while the softening point and viscosity increase. This is due to the high content of asphaltene and resin in natural asphalt, which realizes the colloidal structure modification of the petroleum asphalt. With the increase in the percentage of natural asphalt, the modified asphalt gradually changes from sol–gel to gel, showing an increase in the softening point and viscosity.

The particle size distribution in Figure 2 shows that the particle size of inorganic substances in natural asphalt is controlled within 1–10 μm range, with an average particle size of 6.445 μm. This was achieved through the micronized process, and the particle size distribution, obviously enough, seems to present a normal distribution. On the one hand, as the particle size decreased, the settling speed gradually decreased corresponding to Stokes' Law which states that "when the particle size reaches a balance between gravity and buoyancy, it can be stably suspended without settlement and segregation." On the other hand, the particle size reduction means that the specific surface area of the material increased, which can effectively exert the advantages of modified asphalt with natural asphalt.

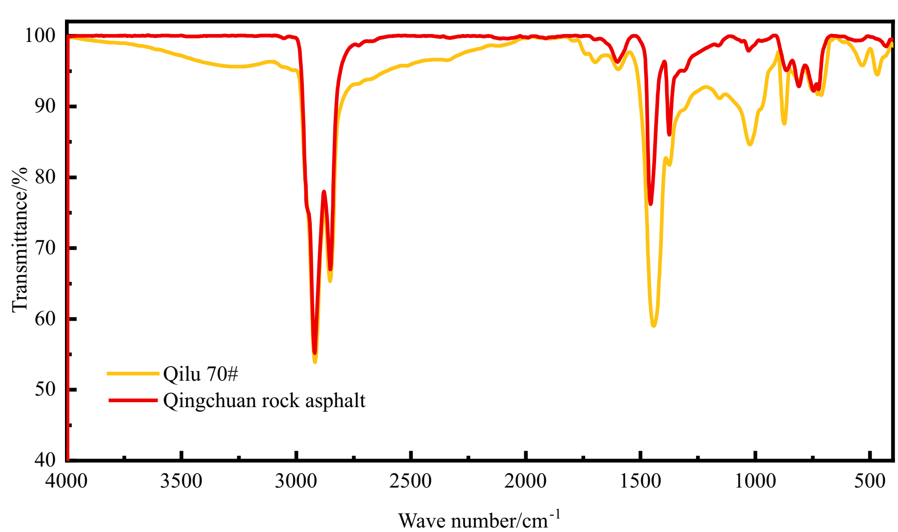

Figure 1: FTIR curve of asphalt.

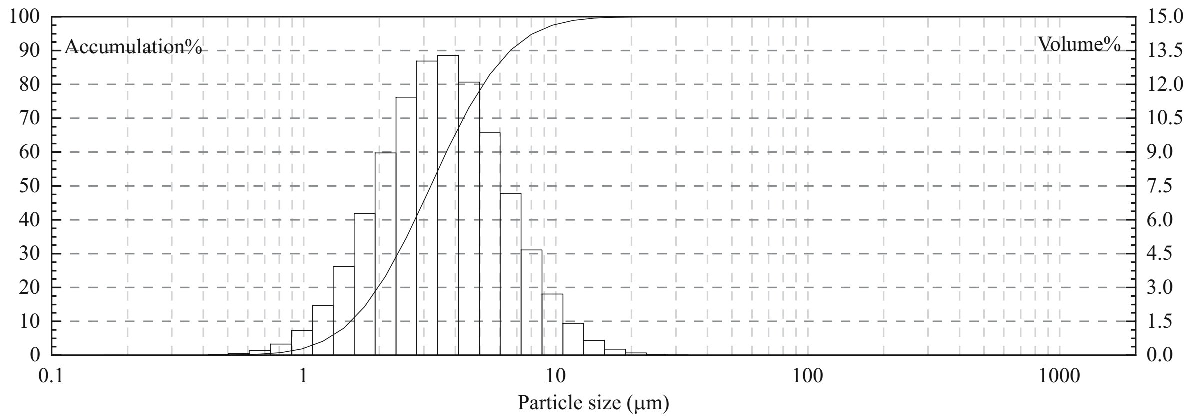

Figure 2: Particle size distribution of inorganic substances in modified asphalt.

Table 2: Test results of modified asphalt with different QRA contents

Items	Unit	QRA content						
		7.5%	10%	12.5%	15%	17.5%	20%	25%
Penetration (25°C, 100 g, 5 s)	0.1 mm	49	42	36.8	31	27	27	19
Softening point	°C	51.5	54	56	58	61.4	64.3	70.5
Viscosity of 135°C	Pa·s	0.925	1.152	1.415	1.841	2.149	3.335	4.715
Viscosity of 155°C	Pa·s	0.401	0.413	0.729	0.789	0.904	1.572	1.726

3 Method of carbon emission calculation

3.1 Objectives and scope

The construction of asphalt pavement is divided into raw material production stage (red box), transportation stage (blue box), and construction stage (yellow box), as shown in Figure 3. This work mainly studies the carbon emission during the production stage of using natural asphalt in modified asphalts, which is the content of the red box.

The boundary of the modified asphalt with natural asphalt's production stage is defined as three links: asphalt mining, transportation, and processing, as shown in Figure 3.

3.2 Life cycle inventory

Figure 3 shows the three main links of the exploitation, transportation, and processing of modified asphalt with natural asphalt and petroleum asphalt. The carbon emissions of modified asphalt with natural asphalt mainly come from the energy consumption of asphalt exploitation, diesel consumption of asphalt transportation, and energy consumption of asphalt processing.

The list of various units of the production stage of modified asphalt with natural asphalt is divided, as shown in Figure 4, taking QRA as an example.

3.3 Calculation model of carbon emission

Argonne National Laboratory of the United States has developed an evaluation model based on excel, and the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) software has also been developed to assess the impact of alternative fuels and advanced vehicle technologies on carbon emissions in the entire fuel cycle process [17]. This is convenient and efficient because of its rich database. The GREET software is used to evaluate the carbon emissions in the raw material production stage of modified asphalt with natural asphalt. The life cycle model of the modified asphalt with natural asphalt is established, and the final output results are obtained through investigating the input parameters required in the model by software calculation.

The production stage of modified asphalt with natural asphalt involves five links: rock asphalt mining, rock

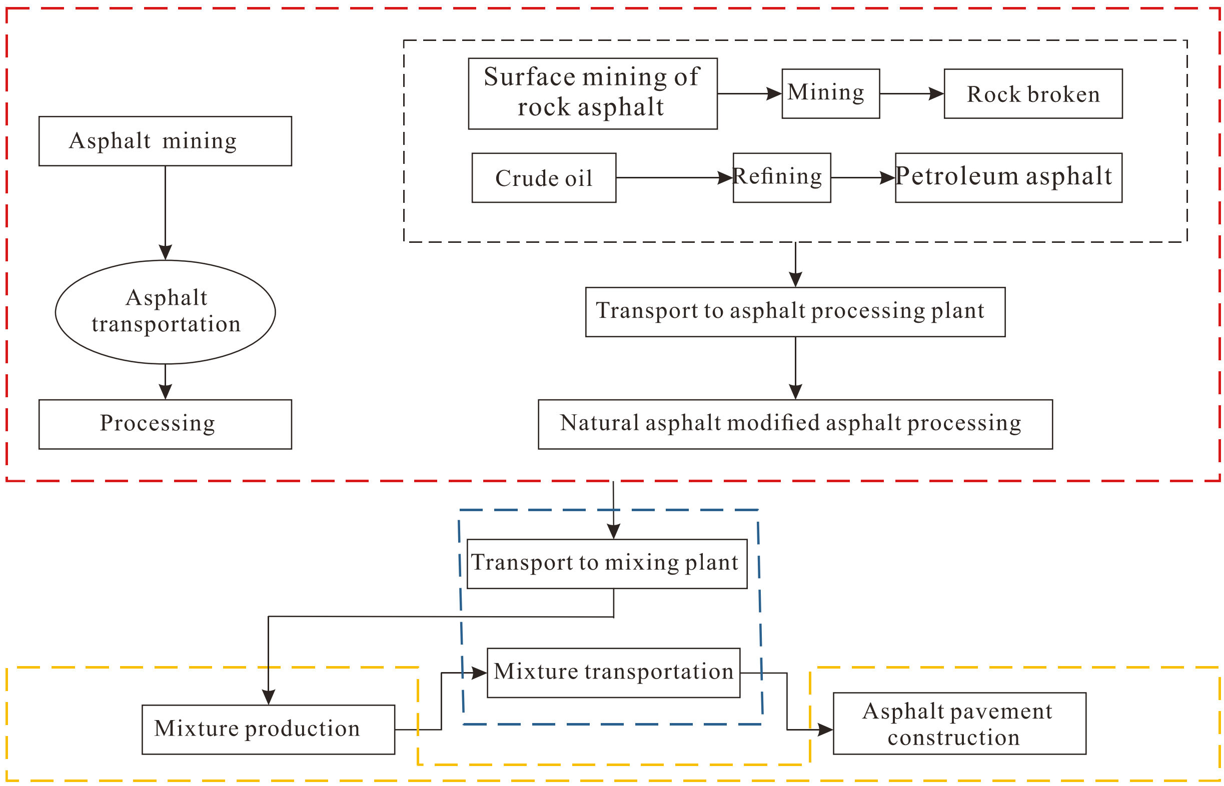

Figure 3: Boundary condition of modified asphalt with natural asphalt.

asphalt transportation, petroleum asphalt production, petroleum asphalt transportation, and modified asphalt with natural asphalt processing. The carbon emission value of each link is calculated as follows.

3.3.1 Petroleum asphalt

3.3.1.1 Link of crude oil production and storage

After a series of treatment of the residual oil from crude oil fine processing, petroleum asphalt is obtained. There is no link of crude oil exploitation and transportation with the existing crude oil of the processing plant as the initial raw material.

3.3.1.2 Link of petroleum asphalt processing

The existing petroleum asphalt refining process stipulates that 6.1515 kg of water, 0.6033 kg of refinery distillate gas, and 7.6062 g of refinery catalyst coke are required according to GREET model to produce 1 MMBtu petroleum asphalt. The share of other energies required by the groups is shown in Figure 5. In addition, 7.29 g CO_2 gas is generated.

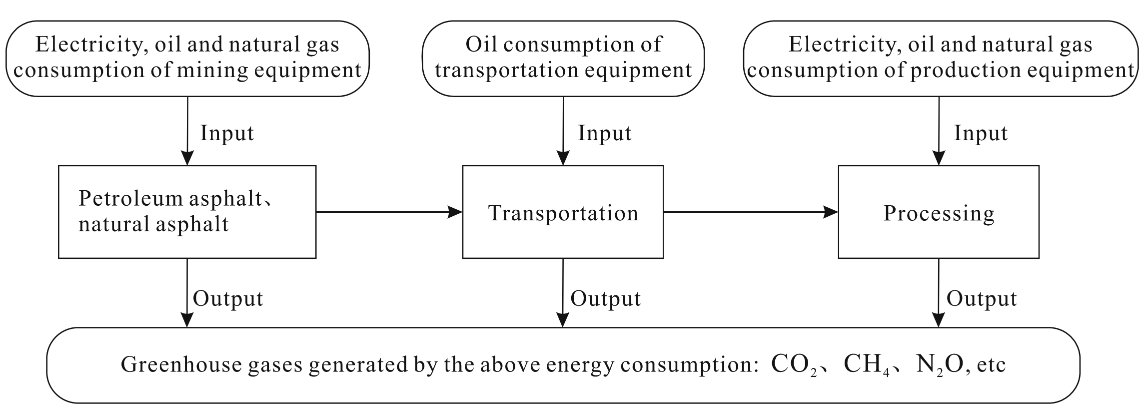

Figure 4: Unit division of the list of production stages of modified asphalt with natural asphalt.

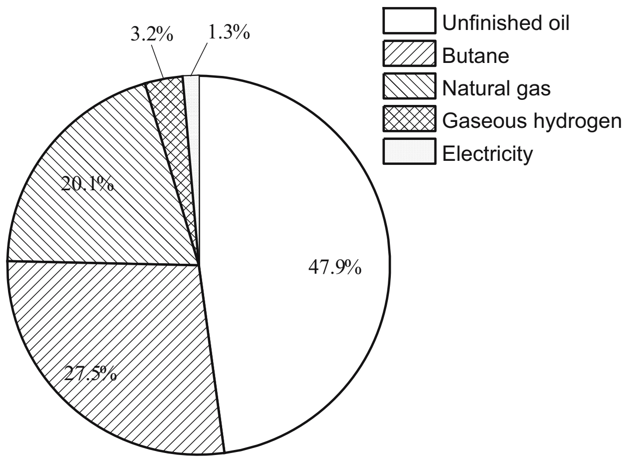

Figure 5: Energy required for producing 1 MMBtu petroleum asphalt.

3.3.2 Modified asphalt with natural asphalt

The links of mining, transportation, and processing involved in the production of modified asphalt with natural asphalt excluding the above link of crude oil production and storage and link of petroleum asphalt processing, are calculated as follows.

3.3.2.1 Link of rock asphalt mining

Large excavators and trucks, whose main input energy is diesel, are used to remove strata, sand, and clay from the skin layer during the surface mining of rock asphalt. The model estimation is relied on in order to ensure the reasonableness of the results in the research, since the energy input data of the mining facilities are confidential. The link of rock asphalt mining is modeled with reference to the coal mining. The default data of energy input for coal mining is already in the GREET, which states that 12.2360 kg of water is required to produce 1 MMBtu rock asphalt. The share of other energies required by the groups is shown in Figure 6.

3.3.2.2 Link of rock asphalt transportation

The rock asphalt is broken into bulk solid after mining, and transported by railway from Qingchuan County, Sichuan Province to the asphalt refinery in Xi'an. The parameters of the railway transportation model are shown in Table 3.

The petroleum asphalt is transported by railway from Rizhao, Shandong Province, to the asphalt refinery in Xi'an using a freight insulating tanker. The thermal insulation is essential during the link of transportation through

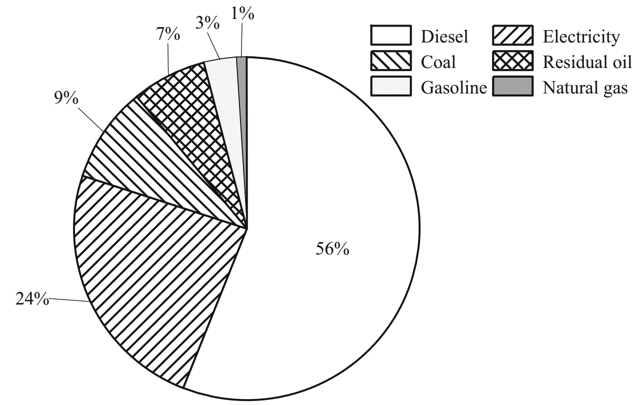

Figure 6: Energy required for producing 1 MMBtu rock asphalt.

fire tube boiler. The fuel used for the fire tube boiler is diesel, fuel oil, and fuel gas. The parameters of the railway transportation model are shown in Table 4.

3.3.2.3 Link of modified asphalt with natural asphalt processing

The carbon emission model of production is established, as shown in Figure 7, where consumption of electricity (2,395,318 kW·h) and natural gas (1,568,350 m^3) in the link of modified asphalt with natural asphalt processing is provided by Xi'an Zhongli Asphalt Co., Ltd.

3.4 Calculation formulas

3.4.1 Equivalent carbon dioxide

The emissions of CO_2, CH_4, and N_2O in the greenhouse gases generated by human activities have the greatest impact on the greenhouse effect according to the assessment report of the Intergovernmental Panel on Climate Change [18]. The greenhouse gas emissions of each link in the production stage of modified asphalt with natural asphalt are calculated by GREET, and the equivalent

Table 3: Railway transportation model parameters of natural asphalt

Parameters	Value
Distance of transportation	462 km
Type of fuel	Diesel
Energy intensity of fuel	0.1973 $J{\cdot}kg^{-1}{\cdot}m^{-1}$
Average speed of transportation	65 $km{\cdot}h^{-1}$

Table 4: Railway transportation model parameters of petroleum asphalt

Parameters	Value
Distance of transportation	1,221 km
Type of fuel	Diesel, fuel oil, fuel gas
Energy intensity of fuel	0.1973 $J \cdot kg^{-1} \cdot m^{-1}$
Average speed of transportation	65 $km \cdot h^{-1}$

carbon dioxide (CO_2e) of each link is calculated by Eq. 1 as follows:

$$CO_2\ e = \text{greenhouse gas tonnage} \times \text{GWP} \quad (1)$$

where global warming potential (GWP) represents the greenhouse gas efficiency. The 100 year GWP values of CO_2, CH_4, and N_2O are 1, 25, and 298.

3.4.2 Carbon emissions

The production stage of modified asphalt with natural asphalt is mainly divided into mining, transportation, and processing. The carbon emission of each link is determined after determining the boundary conditions for the production of modified asphalt with natural asphalt. As shown in Eq. 2, the sum of carbon emissions in each link is the total carbon emissions in the production stage of modified asphalt with natural asphalt [19].

$$M = M_{\text{min}} + M_{\text{tran}} + M_{\text{pro}} \quad (2)$$

where M is the total carbon emission in the production stage of modified asphalt with natural asphalt; M_{min} is the carbon emission of the link of raw materials mining; M_{tran} is the carbon emission of the link of asphalt transportation to the processing plant; M_{pro} is the carbon emission of the link of modified asphalt with natural asphalt processing.

4 Results

The amount of natural asphalt in modified asphalt with natural asphalt is different according to different application requirements of modified asphalt with natural asphalt. The emissions of main greenhouse gas with the content of natural asphalt 10%, 15%, 20%, 25%, 30%, 40%, and 50% are shown in Table 5.

The unit CO_2e of each link in the production stage of petroleum asphalt and 25% modified asphalt with natural asphalt is shown in Table 6.

It can be seen from Table 6 that the CO_2e in the link of rock asphalt mining is only 9.4% of that in the link of crude oil production and storage. The CO_2e in the link of modified asphalt with natural asphalt processing is 44.7% lower than that in the link of petroleum asphalt processing, and that in the link of rock asphalt transportation account for only 1/3 of the one in the link of petroleum asphalt transportation. Therefore, rock asphalt is a low-carbon and much more environment-friendly material than petroleum asphalt as a raw material.

5 Discussion

5.1 Influence of natural asphalt content on carbon emission

The calculated results of equivalent carbon emissions are shown in Figure 8.

As shown in Figure 8, with the content of natural asphalt increasing, the CO_2e of modified asphalt with natural asphalt gradually decreased. Initially, the CO_2e of petroleum asphalt was 355.63 kg $CO_2e \cdot t^{-1}$ in the production stage. However, when the content of natural

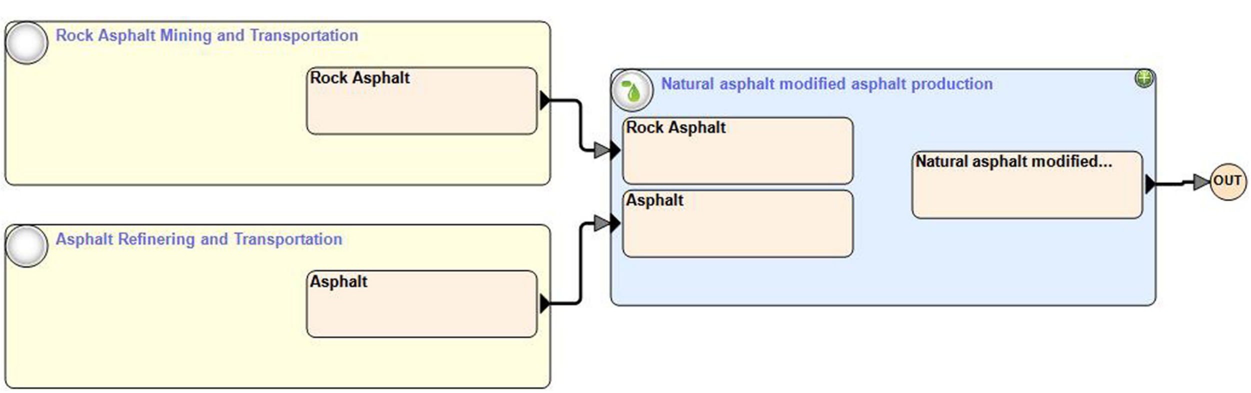

Figure 7: Production model of natural asphalt and modified asphalt.

Table 5: Greenhouse gas emissions of different natural asphalt contents

Types of greenhouse gas		Emissions of greenhouse gas (kg·t^{-1})		
		CO_2	CH_4	N_2O
Petroleum asphalt		267.5994	3.4723	0.0041
Modified asphalt with natural asphalt	10%	293.8405	3.4992	0.0066
	15%	281.1355	3.3268	0.0064
	20%	268.4305	3.1544	0.0062
	25%	255.7255	2.9820	0.0060
	30%	243.0205	2.8096	0.0058
	40%	217.6105	2.4648	0.0054
	50%	192.2005	2.1200	0.0050

asphalt was less than 18%, the CO_2e of modified asphalt with natural asphalt was higher than that of petroleum asphalt in the production stage. This is mainly because the energy consumption in the link of transportation of petroleum asphalt increased in the production stage of modified asphalt with natural asphalt in the model, due to the fact that the processing plant of modified asphalt with natural asphalt is located in Xi'an, and the petroleum asphalt processing plant is located faraway in Shandong. This further increased energy consumption in the production stage of modified asphalt with natural asphalt. Moreover, when the content of natural asphalt is low, the low-carbon emissions of the link of rock

Table 6: CO_2e of petroleum asphalt and modified asphalt with natural asphalt in each link

Link	Carbon emissions (kg·t^{-1})			CO_2e (kg CO_2e·t^{-1})
	CO_2	CH_4	N_2O	
Rock asphalt mining M_{min}	25.0642	0.0392	0.0003	26.1336
Rock asphalt transportation Qingchuan → Xi'an M_{tran}	7.2735	0.0093	0.0002	7.5656
Crude oil production and storage M_{min}	194.4746	3.3571	0.0031	279.3259
Petroleum asphalt processing M_{pro}	73.1248	0.1152	0.0010	76.3028
Petroleum asphalt transportation Rizhao → Xi'an M_{tran}	18.8383	0.0241	0.0005	19.5898
Modified asphalt with natural asphalt processing M_{pro}	32.8128	0.3476	0.0024	42.2180
25% modified asphalt with natural asphalt	/			332.0635
Petroleum asphalt	/			355.6287

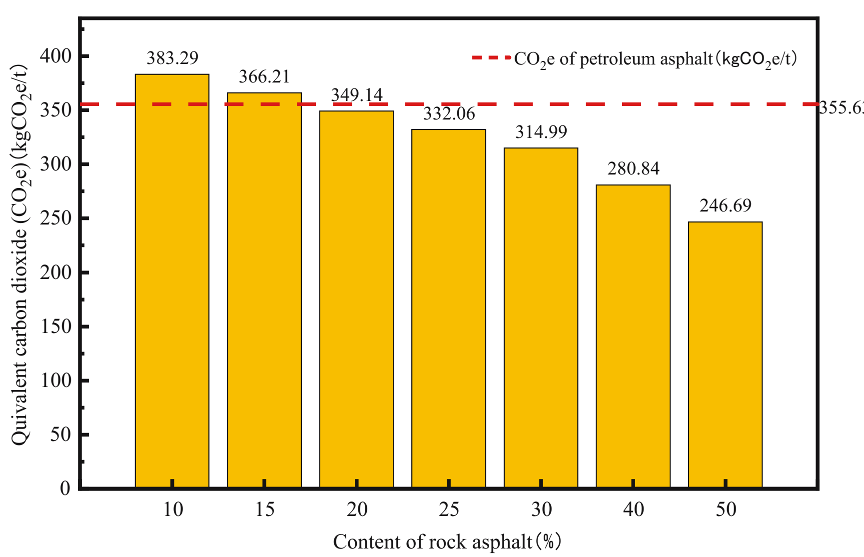

Figure 8: CO_2e of modified asphalt with natural asphalt with different content of natural asphalt.

Table 7: Carbon emission hierarchy and elements

Target hierarchy	Weight coefficient of carbon emission of each link
Rule hierarchy	Proportion of each link in total carbon emissions Scale: Importance of each link
Project hierarchy	Rock asphalt mining; rock asphalt transportation; crude oil production and storage; petroleum asphalt processing; modified asphalt with natural asphalt processing

asphalt mining and transportation are not enough to offset the carbon emissions of the link of modified asphalt with natural asphalt processing, although the energy consumption of rock asphalt mining and transportation is relatively small. However, the CO_2e of modified asphalt with natural asphalt is smaller than that of petroleum asphalt as the content of rock asphalt continuously increased. When the content reached 30%, the CO_2e of modified asphalt with natural asphalt was 11.4% lower than that of petroleum asphalt.

5.2 Calculation of carbon emission weight of modified asphalt with natural asphalt

In order to understand the impact of the carbon emissions of each link in the asphalt production stage on the total carbon emissions in the production stage, and to provide basic data for energy conservation and emission reduction in the production stage, the AHP was used to analyze the carbon emission weight of each link of modified asphalt with natural asphalt production stage. The calculation process is as follows.

5.2.1 Establish hierarchical structure model

The hierarchical structure model of the case is shown in Table 7.

5.2.2 Construct judgment matrix

The judgment matrix of the target hierarchy $Y_{5\times5}$ is obtained, as follows, combined with the weight coefficient of carbon emission of each link of modified asphalt with natural asphalt, and the importance scale of the comparison between two elements.

$$Y_{5\times5} = \left\{\begin{matrix} 1 & 2 & \frac{1}{9} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{2} & 1 & \frac{1}{9} & \frac{1}{6} & \frac{1}{7} \\ 9 & 9 & 1 & 8 & 6 \\ 3 & 6 & \frac{1}{8} & 1 & \frac{1}{2} \\ 4 & 7 & \frac{1}{6} & 2 & 1 \end{matrix}\right\}$$

5.2.3 Calculation results

The function of eigenvalue and eigenvector is called in the Math CAD software. The eigenvalue of modified asphalt with natural asphalt in the production stage and the eigenvector ($\vec{w}$) corresponding to the maximum eigenvalue ($\lambda_{\max}$) are as follows:

$$\mathrm{Eigenvals}\left[\left\{\begin{matrix} 1 & 2 & \frac{1}{9} & \frac{1}{3} & \frac{1}{4} \\ \frac{1}{2} & 1 & \frac{1}{9} & \frac{1}{6} & \frac{1}{7} \\ 9 & 9 & 1 & 8 & 6 \\ 3 & 6 & \frac{1}{8} & 1 & \frac{1}{2} \\ 4 & 7 & \frac{1}{6} & 2 & 1 \end{matrix}\right\}\right] = \left\{\begin{matrix} 5.344 \\ -0.118 + 1.341i \\ -0.118 - 1.341i \\ -0.011 \\ -0.097 \end{matrix}\right\}$$

$$\mathrm{Eigenvec}\left[\left\{\begin{matrix} 1 & 2 & \frac{1}{9} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{2} & 1 & \frac{1}{9} & \frac{1}{6} & \frac{1}{7} \\ 9 & 9 & 1 & 8 & 6 \\ 3 & 6 & \frac{1}{8} & 1 & \frac{1}{2} \\ 4 & 7 & \frac{1}{6} & 2 & 1 \end{matrix}\right\}, 5.344\right] = \left\{\begin{matrix} 0.075 \\ 0.048 \\ 0.944 \\ 0.176 \\ 0.264 \end{matrix}\right\}$$

That is, $\lambda_{\max} = 5.344$ and $\vec{w} = (0.075\ 0.944\ 0.944\ 0.264)^T$

Table 8: Carbon emission weight of natural asphalt and modified asphalt in each link of production stage

Content of rock asphalt (%)	Rock asphalt mining (%)	Rock asphalt transportation (%)	Petroleum asphalt processing (%)	Petroleum asphalt transportation (%)	Modified asphalt with natural asphalt processing (%)
25	5.0	3.2	62.6	11.7	17.5
50	7.6	3.6	57.0	11.9	19.9

5.2.4 Consistency check

Coincident indicator of matrix CI $=\frac{\lambda - n}{n-1} = \frac{5.3442 - 5}{4} = 0.0861$; When $n = 5$, mean consistency index RI = 1.12. Random inter-consistency ratio CR $= \frac{\text{CI}}{\text{RI}} = \frac{0.0861}{1.12} = 0.0768 < 0.1$.

It can be seen from the above calculation results that the AHP calculation results have satisfactory reliability.

5.2.5 Weight of carbon emissions

Normalize the object matrix $\lambda_{\max}$ and its corresponding $\vec{w}$.

$\overline{\vec{w}} = \vec{w}/\sum_{j=1}^{5} w_j = (0.050 \quad 0.032 \quad 0.626 \quad 0.117 \quad 0.175)^T$, where w_j is the element of $\vec{w}$. The weight coefficient of carbon emission of each link of modified asphalt with natural asphalt in production stage with 25% and 50% content is shown in Table 8.

As shown in Table 8, the links of petroleum asphalt processing and transportation have the highest weight of carbon emissions, accounting for 74.3% and 68.9%, with 25% and 50% content of rock asphalt, respectively, in the production stage of modified asphalt with natural asphalt. However, the link of rock asphalt mining, rock asphalt transportation, and modified asphalt with natural asphalt processing only accounted for 25.7% and 31.1% of the carbon emissions in the whole production stage. The weight of carbon emission of petroleum asphalt decreased with the increase in rock asphalt content, and this is the clear dominant factor. Three solutions should thus be adopted: increasing the content of rock asphalt; reducing energy consumption in asphalt production stage with low-carbon energy saving technology; and shortening transportation distance of petroleum asphalt, such as setting the processing plant of modified asphalt with natural asphalt near the processing plant of petroleum asphalt.

6 Conclusion

The modification mechanism of QRA was analyzed, and the carbon emission of modified asphalt with natural asphalt during the production stage was expounded based on LCA. The carbon emission calculation model in the asphalt production stage was established, the carbon emissions of each link were calculated through GREET software, and the carbon emission weights of each link of modified asphalt with natural asphalt were studied through the AHP. The conclusions drawn are as follows:

1. QRA has a high content of asphaltene and resin, which can help realize the colloidal structure modification of the petroleum asphalt. Furthermore, natural asphalt and petroleum asphalt have good compatibility, which is a physical blending process, and the polar functional groups C=O, Si–O, C–O contained in natural asphalt make modified asphalt with natural asphalt have good peeling resistance and water stability.
2. The CO_2e in QRA extraction process is only 9.4% of the production of crude oil, and the CO_2e in the modified asphalt with natural asphalt processing process is 57.0% lower than that in the petroleum asphalt refining process. In addition, the carbon emissions from QRA transportation process only account for 1/3 of that from petroleum asphalt transportation process.
3. When QRA content exceeds 18%, the CO_2e of modified asphalt with natural asphalt in the production stage is lower than that of petroleum asphalt, and when the content reaches 30%, the CO_2e of modified asphalt with natural asphalt is 11.4% lower than that of petroleum asphalt.
4. The highest weight of carbon emissions is in the production and transportation process of petroleum asphalt. When QRA content is 25% and 50%, the weight of carbon emission reaches 74.3% and 68.9%, respectively.

Funding information: This research was funded by the Science and Technology Project of Shaanxi Department of Transportation (No. 20-43K).

Author contributions: Xiu-feng Zhang and Yun Zeng proposed the idea of the study, and Cheng-xue Zhang established GREET carbon emission model. Yong-nian Feng provided the energy data required for model calculation and analyzed the calculation results. Ling Zhang prepared the manuscript with contributions from all co-authors. The authors applied the SDC approach for the sequence of authors.

Conflict of interest: The authors state no conflict of interest.

References

[1] Li GN, He L, Rao ZP. Research on energy consumption and carbon dioxide emission of expressway maintenance phase based on life cycle assessment. Highway. 2018;63(5):269–75. https://kns.cnki.net/kcms/detail/11.1668.U.20180516.2039.108.html.

[2] Kuai HD, Xue JS, Tang H, Chen F. Quantitative study on energy consumption of road material in china based on life cycle. Road Mach Constr Mech. 2018;35(10):112–7.

[3] Chen J, Zhao F, Liu Z, Ou X, Han H. Greenhouse gas emissions from road construction in China: A province-level analysis. J Clean Prod. 2017;168(Dec. 1):1039–47. doi: 10.1016/j.jclepro.2017.08.243

[4] Mangum M. Asphalt Paving Sector Presentation. Health Effects of Occupational Exposure to Emissions from Asphalt/Bitumen Symposium. Germany: Dresden; 2006.

[5] Zhang JX, Su C, Wang C, Jing P, Hou Y. Review of energy-saving and emission-reduction issues and technologies in the construction of road infrastructure. J Beijing Univ Technol. 2022;48(3):243–60. https://kns.cnki.net/kcms/detail/11.2286.T.20220215.1708.016.html.

[6] Krantz J, Lu W, Johansson T, Olofsson T. Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions. J Clean Prod. 2017;143(Feb. 1):980–8. doi: 10.1016/j.jclepro.2016.12.023.

[7] Yang Y. Study on construction technology of low carbon and thin paving for high grade asphalt pavement. Tianjin Constr Sci Technol. 2018;28(3):54–6.

[8] Hu JR. Research on Low Carbon Construction Technology of Asphalt Pavement Based on Energy Consumption Calculation. Dissertation. Xian: Xi'an University of Architecture and Technology; 2019.

[9] Peng B, Tong X, Cao S, Li W, Xu G. Carbon emission calculation method and low-carbon technology for use in expressway construction. Sustainability-Basel. 2020;12(8):1–18. doi: 10.3390/su12083219.

[10] Thives LP, Ghisi E. Asphalt mixtures emission and energy consumption: A review. Renew Sust Energ Rev. 2017;72:473–84. doi: 10.1016/j.rser.2017.01.087.

[11] Wang QZ, Wang NN, Tseng ML, Huang YM, Li NL. Waste tire recycling assessment: Road application potential and carbon emissions reduction analysis of crumb rubber modified asphalt in China. J Clean Prod. 2019;249:119411. doi: 10.1016/j.jclepro.2019.119411.

[12] Hu K, Sun HX. Study on energy consumption and carbon emission of cold mixing regeneration technology in asphalt emulsion plant. North Commun. 2020;326(6):26–9. doi: 10.15996/j.cnki.bfjt.2020.06.008.

[13] Zhang J, Chen M, He Y, You XJ, Zhao W, Ling MQ, et al. First discovery of the tectono-strata-bound type natural asphalite in the Guangyuan, Sichuan Province. 2023;50(1):289–90. https://kns.cnki.net/kcms/detail/11.1167.P.20220314.1839.004.html.

[14] Wang YN, Li B, Ren XY, Zhang ZH, Chen ZQ. Analysis of SBS modified asphalt with different aging time by regenerated infrared spectroscopy. J Mater Sci Eng. 2020;38(4):643–7, 565. doi: 10.14136/j.cnki.issn1673-2812.2020.04.023.

[15] Meng XC. Study on quantification of energy consumption and carbon emission during the period of asphalt pavement construction. Master dissertation. Beijing: Beijing Jiaotong University; 2020.

[16] Gao F. Study on quantitative analysis of energy consumption and emissions during the period of asphalt pavement construction based on LCA. Master dissertation. Chongqing: Chongqing Jiaotong University; 2016.

[17] Bergerson JA, Kofoworola O, Charpentier AD, Sleep S, Maclean HL. Life cycle Greenhouse gas emissions of current Oil Sands Technologies: surface mining and in situ applications. Env Sci Technol. 2012;46(14):7865–74. doi: 10.1021/es300718h.
[18] Wang HW, Liu HX, Wang SC. Research on effect of environment in highway tunnel on emission of diesel engine. China J Highway Transp. 2003;(4):99–101. doi: 10.19721/j.cnki.1001-7372.2003.04.022.
[19] Wong E, Ho D, So S, Tsang CW, Chan EMH. Life cycle assessment of electric vehicles and hydrogen fuel cell vehicles using the GREET model—A comparative study. Sustainability-Basel. 2021;13(9):4872. doi: 10.3390/su13094872.