Environmental Benefit Analysis of Hot Central Plant Recycling Asphalt Pavement Based on LCA

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Abstract. In order to determine the energy-saving and emission-reduction effects of the application of hot central plant recycling in the highway asphalt pavement maintenance project, this study selects a road section of overhaul project in Tongren as the analysis object, and adopt the environmental benefit analysis method based on life cycle assessment to analyze the energy consumption and environmental emissions of hot central plant recycling and hot mix asphalt. The comparison shows that the application of hot central plant recycling in highway asphalt pavement maintenance project has good energy saving and emission reduction benefits, and the aggregate and asphalt production stage are the main components. Moreover, under the condition of ensuring the road performance of recycled pavement, with the increasing proportion of reclaimed asphalt pavement, the environmental benefit of recycled pavement is higher. While with the increase of reclaimed asphalt pavement transportation distance, the environmental benefit presents a downward trend.

1. Introduction
The transportation sector greatly influence the sustainable development of a society, contributing to air pollution from vehicular emissions, global warming, consumption of energy resources, disturbance of natural space from infrastructure construction, and noise pollution[1]. In the recent 40 years, highway construction has made significant progress in China. According to the statistics of Ministry of Transport of the People’s Republic of China, by the end of 2019, the total mileage of China’s roads reached 5.0125 million kilometers. Among them, the mileage of highways is 149,600 kilometers [2]. As time passed, the highway completed early has entered the repair stage successively, and the amount of reclaimed asphalt pavement (RAP) produced in pavement maintenance engineering is also increasing.

RAP is a mixture, including aged asphalt binder and aggregates produced by recycling hot mix asphalt (HMA) known as the most common recycled materials used in flexible pavements[3]. The high-priced original binder can be replaced with RAP as a less-costly binder to prepare eco-friendly pavements [4]. For example, using RAP as waste material in pavement structure decrease the emission of greenhouse gas into the atmosphere leading to improvement in the environment health [5-6]. In order to reduce environmental burden associated with asphalt binder, a number of sustainable strategies have been developed and used in the paving industry over the years, including warm-mix asphalt (WMA) and partial replacement of asphalt binder with bio-binder or other industry by product [7-8]. Currently, HMA is widely used as surface material for roadway, airfield, tunnel, and bridge deck [9]. However, there is a lack of accurate and comprehensive quantitative evaluation of how energy use and greenhouse gas emission are impacted by the use of recycled materials [10].

Life cycle assessment (LCA) provides a comprehensive and holistic platform for environmental assessment of sustainable practices. It can be used to quantify environmental impact of various stages
in the pavement’s life cycle, including material acquisition, plant production, transportation, construction and maintenance, usage, and end-of-life. The LCA method has been extensively used in different studies to assess environmental impact of pavements [9]49-150. Most of these studies focus on using LCA method to quantify the GHG (greenhouse gas) emission of asphalt pavement in usage stage [11]; compare the energy consumption and GHG emission of different maintenance activities that significantly affect options between asphalt and concrete [12]; evaluate life-cycle environmental and economic impacts of flexible pavements with varying amounts of RAP from 8% to 50% [13]; analyze environmental sustainability of three asphalt pavements at all stages from raw materials to the end of service life [14]; quantify GHG emission from asphalt pavements containing recycled asphalt pavements from a time perspective [9]. Although a number of studies have used LCA to analyze environmental impact of using RAP in asphalt mixture, previous studies neglected the environmental impact of the acquisition process of RAP (milling from old pavement), transportation of RAP to processing plant, and the reprocessing or pretreatment of RAP in processing plant.

Thus, the study is based on the existing research results, fully considering the energy consumption and GHG emission impacts at all stages in the pavement’s life cycle. And then, combined with the real project, compare the life cycle energy consumption and environmental emissions of hot central plant recycling (HCPR) and HMA, showing the positive significance of HCPR in practicing the concept of ecological and environmental protection.

2. Research methodology

2.1. Goal and scope of LCA

HCPR refers to the technology of “crushing and screening RAP in the mixing plant, heating and mixing it with new mineral material, new asphalt and asphalt regenerant in a certain proportion to form asphalt pavement” [15]. This study uses process-based LCA method of HCPR to quantify the energy consumption and environmental emissions of RAP milling recovery, raw material production, asphalt mixture production and pavement construction stages, evaluate its impact on resource destruction and ecological environment. The system boundary of the LCA of HCPR is shown in Figure 1.

2.2. Energy consumption inventory analysis

Life cycle energy consumption inventory analysis methods mainly include measurement method, theoretical method and quota method, among which quota method integrates the characteristics of measurement method and theoretical method, and is the most commonly used and effective energy consumption calculation method [16]. It takes the specific mechanical equipment, operating vehicle parameters and use frequency within the quota scope as the core, which can reflect the construction process and energy consumption level under the social average level. Firstly, determine the number of mechanical shifts per unit output according to the technological process specified in the Budget Quota.
of Highway Maintenance Project and Cost Quota of Machine Shift for Highway Maintenance Engineering of a province; secondly, basing on the energy consumption parameters of machine shift and net calorific value (NCV) obtained from the statistical results released by Intergovernmental Panel on Climate Change, to calculate the energy consumption of each stage by using formula (1); finally, the total energy consumption of the production unit of recycled mixture is calculated by summation.

\[ E = \sum (Q_i \cdot NCV_i) \]  

(1)

In the formula: \( Q_i \) is the unit fuel consumption (kg) of type \( i \) mechanical equipment; \( NCV_i \) is the net calorific value (MJ/kg) of the fuel used for the corresponding mechanical equipment.

2.3. Environmental emission inventory analysis

The calculation of the emissions of GHG and the environmental impacts by them in the whole life cycle of HCPR is relatively complicated. The calculation generally uses the environmental emission inventory analysis method based on IPCC emission factor method with strong applicability and simple form: first of all, on the premise of determining the default emission factors (as shown in Table 1) of common fuel combustion under the assumption of 100% oxidation of fuel, to calculate the emissions of various substances; second, determine the characteristic factor of each impact factor (as shown in Table 2); finally, calculate the total amount of various environmental emissions of each stage through formula (2).

\[ EP = \sum (Q_i \cdot EF_i) \]  

(2)

In the formula: \( EP \) is the total characteristic emission of the environmental impact of global warming; \( Q_i \) is the emission amount of type \( i \) material; \( EF_i \) is the characteristic factor of the \( i \) emission.

Table 1. Default emission factor of fuel combustion based on net calorific value (mg/MJ)

| Fuel Type  | Net Calorific Value (MJ/Kg) | CO₂       | CH₄       | N₂O       |
|------------|-----------------------------|-----------|-----------|-----------|
| Diesel Oil | 43.0                        | 74100.00  | 3.00      | 0.60      |
| Heavy Oil  | 40.4                        | 77400.00  | 3.00      | 0.60      |

Table 2. Impact factor and characteristic factor

| Impact Factor | Characteristic Factor or Unit | Characteristic Factor |
|---------------|------------------------------|-----------------------|
| CO₂           | kg equivalent CO₂            | 1.00                  |
| CH₄           |                              | 25.00                 |
| N₂O           |                              | 298.00                |

The data sources of life cycle energy consumption and environmental emission inventory were obtained from the online database of budget quota of highway maintenance engineering, cost quota of machine shift, peer-reviewed journal, conference papers, and reports published by government agencies or academic institutions that met criteria for quality and relevance.

3. Case study of asphalt pavement

Overhaul project of a road section of provincial highway S303 in Tongren, 10 kilometers long, is a typical section of mountainous highway in Guizhou Province. The design speed of the road section is 20 km/h, the width of the subgrade is 6.5m. The distance from the maintenance section to the processing plant is 50 kilometers, the distance to the asphalt mixing plant is 50 kilometers, and the distance to the spoil ground is 75 kilometers. The original pavement structure is 4cm thick AC-13 ordinary asphalt concrete surface layer, 15cm thick graded gravel base layer, and the main diseases of the original pavement are network cracking, longitudinal cracking, transverse cracking, and deformation, etc. After pavement maintenance, the surface course is 4cm thick AC-13 plant mixed hot recycled mixture, and the base course is 15cm thick graded gravel. The AC-13 plant mixed hot recycled asphalt mixture contains 3.41% asphalt binder (30% RAP, the content of asphalt in RAP is 4.5%), 67.55% aggregate, and 0.09% asphalt regenerant.
4. Results and discussion

4.1. Quantitative analysis of energy consumption
The LCA of HCPR includes four stages: RAP milling recovery, raw materials production, asphalt mixture production and pavement construction. The energy consumption and environmental emission of each stage mainly come from the combustion of diesel, heavy oil and other fuels and power consumption of relevant mechanical equipment. Based on this, the consumption and emission at each stage of paving 1 ton of AC-13 plant mixed hot recycled asphalt mixture is calculated by substituting the inventory analysis formula (1) and (2). In order to fully understand the energy consumption difference between HCPR and HMA, the environmental emissions of AC-13 asphalt mixture in each stage of its life cycle are calculated in the same way, so as to evaluate the energy saving and emission reduction effect of HCPR reasonably and objectively (as shown in Figure 2).

According to the above quantitative analysis results, the total energy consumption of HCPR is 643.95 MJ/ton. Compared with the 741.67 MJ/ton consumed by HMA, the total energy consumption is saved by 97.72 MJ/ton, and the energy saving ratio is 13.2%. This is reflected in: (1) due to the shortening of RAP transportation distance, the energy consumption of RAP milling recovery stage is reduced by 28.02 MJ/ton; (2) with the addition of RAP, 13.53 kg of asphalt and 276.89 kg of new aggregate can be saved for each ton of HCPR mixture, saving a total of 75.56 MJ/ton of energy consumption, in which the energy consumption of new asphalt production stage accounts for the largest proportion.

4.2. Quantitative analysis of environmental emissions
Based on the energy consumption calculation results of each stage, combined with the default emission factors of diesel, heavy oil, and electric power and the characteristic factor of each emission factor, substituting into equation (2), to calculate the total environmental emissions at each stage of the life cycle of AC-13 HCPR and HMA (the calculation results are shown in Table 3). The results show that the total environmental emissions of HCPR are 41348.10 g equivalent CO₂. Compared with HMA, the emission is reduced respectively 4426.39 g equivalent CO₂, and the emission reduction ratio is 9.97%, which is due to the shortening of RAP transportation distance and the saving of asphalt and aggregate as well.

4.3. Effects of RAP content and transport distance
In order to clearly quantify the energy saving and emission reduction effect of RAP with different
proportion on HCPR, this study calculate the energy consumption and environmental emissions with different RAP percentages (varied from 10% to 50%). The results in Table 4 clearly show that the higher the RAP content is, the less the energy consumption and environmental emissions are, and the benefits of energy saving and emission reduction are gradually increasing. However, with the introduction of RAP, asphalt pavement might have the stronger tendency toward deterioration, is more susceptible to fatigue, longitudinal cracking, and transverse cracking [18], resulting in the shorter service life than asphalt pavement with virgin materials [9]. Thus, in order to achieve the effect of energy saving and emission reduction, RAP cannot be blindly increased.

Table 4. Influence of RAP blending ratio on environmental benefits

| RAP Percentages (%) | Energy Consumption (MJ/ton) | Energy Saving (%) | Environmental Emissions (g/ton) | Emission Reduction (%) |
|---------------------|----------------------------|------------------|-------------------------------|-----------------------|
| 10%                 | 690.42                     | 6.91%            | 4153.86                       | 6.41%                 |
| 20%                 | 667.19                     | 10.04%           | 4074.50                       | 8.19%                 |
| 30%                 | 643.95                     | 13.18%           | 3995.24                       | 9.97%                 |
| 40%                 | 620.70                     | 16.31%           | 3916.13                       | 11.76%                |
| 50%                 | 597.44                     | 19.45%           | 3836.94                       | 13.54%                |

To make up for the existing research gaps, understand the environmental burden of RAP transportation stage, this study considers the environmental benefits of different distances from the processing plant to the construction site. It is worth noted that the data in Figure 3 shows that with the increase of transportation distance, the environmental benefits brought by RAP will be continuously offset. When the transportation distance is too long (over 70 kilometers), the environmental benefits will be negative, which shows the importance of strictly controlling the transportation distance of RAP and recycled asphalt mixture.

5. Conclusions
The study proposes to use quota data to calculate the environmental benefits of RAP milling and transportation, which solves the research gap that lacks consideration of energy consumption and environmental emissions during RAP transportation stage. The case study has shown that the application of HCPR can effectively improve the energy-saving and emission-reduction effects of RAP milling and recycling, recycled mixture production and recycled road paving. And as RAP content increases, the environmental benefits increase accordingly. However, with the increase of RAP transportation distance, the environmental benefits of RAP will continue to decrease, and may even appear negative. Therefore, it is necessary to pay attention to improve the proportion of RAP, shorten the distance between processing plant and maintenance section, so as to further reduce the energy consumption of HCPR.

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