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The Life Cycle Energy Consumption and Emissions of Asphalt Pavement Incorporating Basic Oxygen Furnace Slag by Comparative Study

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Abstract: Basic Oxygen Furnace Slag (BOF), as alternatives for aggregate in asphalt pavement construction, is beneficial to the environment by reducing land occupation and resource consumption. However, the quantitative effects on energy consumption and emissions reduction remains poorly understood due to the unavailability of local life cycle inventory. Therefore, its LCI needs to be built by accounting for the properties of BOF aggregate in terms of high porosity and dust content in BOF, the rainy interference condition that reducing efficiency in production, and transportation distance. Here we investigated the life cycle energy consumption and global warming potential (CO2-eq emission) of asphalt pavement incorporating BOF aggregate by performing a case study with uncertainty analysis. Five scenarios were elaborated and performed in the case study. The results show that the energy required for BOF production is 0.024 MJ/kg, approximately half the energy required for crushed stone of 0.044 MJ/kg. The pavements with BOF can reduce up to 12% of emission compared to ordinary pavement. Considerably more negative impacts of rainy weather on energy consumption of BOF than natural crushed stone can be concluded. Monte Carlo simulation indicates that the order of magnitudes of the energy values were varied, from materials extraction as the maximum contributor to transportation. The benefits for BOF utilization are gradually offset by increased transport distances and the displacement ratios of fine crushed stones, due to the increase in fuel and resource consumption for mixing, construction, and transportation.

Keywords: Basic Oxygen Furnace Slag (BOF); energy consumption; global warming potential (GWP); life cycle assessment; rainy interference condition; production efficiency

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1. Introduction

Road construction has an adverse effect on climate change. It accounts for around 28% of global energy consumption and approximately 22% of global equivalent CO_2 emission [1]. The GHG emission is expected to be up to 1.108 billion by 2030 in China [2]. New materials and strategies that can reduce the life cycle energy consumption and GHG emissions have become an urgent need for highway construction projects.

The concrete is usually the most energy and emission-intensive output in road construction by exhausting numerous natural resources such as asphalt and minerals. Extensive studies have been carried out by using Life Cycle Assessment (LCA) on highway construction projects [3]. Replacement of natural resources by using metallurgical solid waste in concrete is one of the effective approaches for the alleviation of energy consumption and emission reduction [4]. Researchers have made great contributions to the utilization of metallurgical slag in concrete [5]. A range of products prepared with slag

have been used in concrete, such as aggregates, ground active fillers, and artificial sand. Compared to the grinding of fillers, which requires a large amount of processing energy, the preparation of aggregates from metallurgical slag is much simpler. Besides, the aggregate usually accounts for more than 90% in asphalt concrete and 50% in cement concrete by weight. The environmental effects of using metallurgical slag as aggregates are predicted to be more significant. A comparative life cycle assessment was carried out for cement concrete road pavements with fly ash and steel slag [1]. The emission reduction effect by using alternative aggregates with EAF in concrete decreases significantly, but also largely depends on transportation distance in Greece. It is believed that the type of slag processing should be considered after the LCA analysis of pavements incorporating slag [6].

Basic Oxygen Furnace Slag (BOF) is one of the main byproducts during metallurgical operation. The BOF is an appropriate auxiliary aggregate for asphalt pavement for its dense texture and good adhesion to asphalt, rather than the pitted texture of EAF aggregate [7,8]. Surprisingly, few studies are related to the energy consumption and GHG emission when BOF is used in asphalt pavement. The quantitative environmental effects of BOF utilization in asphalt pavement remain poorly understood. Basically, there are two aspects to be studied:

1. The unavailability of local life cycle inventory of BOF aggregate

Some researchers believe that steel slag aggregate production requires minimal energy consumption. Its contribution to the environmental impact of the produced pavement is expected to be limited to resource use, since the energy consumption from aggregate production is relatively low [9]. However, it was shown that aggregate production is responsible for 50% of the total greenhouse gas emission in the construction of both asphalt and concrete pavements [3].

The significant difference in processing conditions from natural aggregate also makes it an urgent need to build a local life cycle inventory. The treatment process for raw BOF is divided into crushing, screening, and washing. Due to the presence of steelmaking dust and sludge, the dust content of BOF is quite high and difficult to desorb. It is necessary to set up washing equipment, resulting in extra energy consumption and reduction in efficiency.

2. Unclear sensitive effects from transportation distance

The transportation phase is an important life cycle stage for BOF. Transportation of BOF aggregates largely affects the total energy consumption. Depending on local availability of materials, road transportation may vary accordingly. Road construction and M&R projects are commonly site specified. The location of the project is determined mainly depending on the availability of materials such as crushed aggregate. For the BOF aggregate, it is only procured from a metallurgical manufacturer. The specific gravity of BOF aggregates usually reaches up to 3.2 $g.cm^{-3}$, which is almost 20% more than that of natural aggregates. The discrepancy in gravity becomes more considerable when the aggregate is wet, due to quenching and washing treatments. In the wet condition, the high porosity nature of BOF aggregate is able to absorb up to 3% of the weight of water. Therefore, the wet BOF aggregate would take up approximately 30% extra transportation capacity.

Life cycle assessment is a well-known tool, covered by international standards, that can be used to compare alternatives in order to improve the environmental impact of pavement construction. Using LCA tools, energy consumption and global warming potential (CO_2-eq) can be identified in all of the pavement life cycle stages. The objective of this paper is to collect, organize, and analyze asphalt pavement construction data, integrating across life-cycle stages, for the calculation of GWP and energy consumption associated with material extraction, production, and construction life-cycle phases of a pavement project with a case study.

2. Materials and Applications

2.1. Goal and Scope

LCA was applied as a basic method in this study to calculate and compare the environmental emissions and energy consumption between asphalt pavement with and without BOF. The LCA follows a "cradle-to-gate" approach in accordance with ISO 14040 [10] and 14044 [11]. This research implements 1 km asphalt pavement per lane in one direction as a functional unit.

The system boundary includes materials extraction, transportation, pavement construction phases, usage, Maintenance and Rehabilitation (M&R), and end-of-life as a generic pavement life cycle [12], as shown in Figure 1. There are several published papers indicating that BOF-prepared asphalt pavement shows comparable or even better performance than conventional pavement [13–15]. The use phase impacts are mainly derived by traffic information, fuel consumption of vehicles, and pavement–vehicle interactions. Usage phase is always excluded in life cycle assessments [16], mostly for its overwhelmingly significant environmental impact compared to the other phases [17]. The BOF production and melting process is also set out of boundary for its huge energy exhaustion [18]. Due to the research scope, data availability, and quality, a comparative study was conducted mainly of the material extraction, transportation, mixing, and construction phases. It is based on the assumption that pavements with or without BOF would be subject to the same construction work and service life after construction. Whenever the life of pavement ends, it turns to RAP and is commonly disposed without recycling. Therefore, the environmental burden of RAP is not considered.

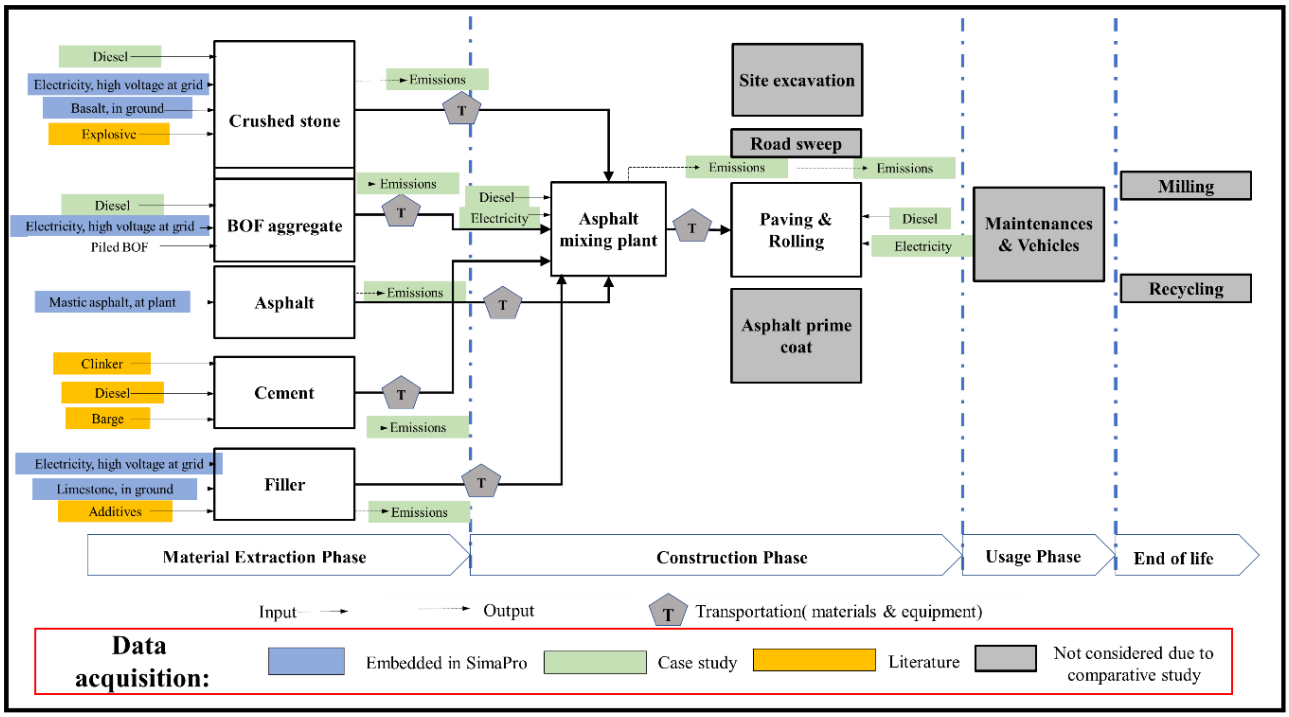


Figure 1. System boundary of the study.

As shown in Figure 1, during the stage of aggregate production, all the BOF were considered to be industrial solid waste. Allocation of industrial byproduct such as BOF seems to apply excessive environmental impacts. It is inappropriate for the promotion of byproducts [19]. The process involved in metallurgical operation, such as pre-crushing and cooling, is therefore not included in the system boundary. In the stage of transportation, the load capacity of the truck was chosen to be 30 t. Transportation in the system boundary included going from the manufacturer to the quarry, from the manufacturer to the plant

with raw materials, and from the plant to the construction site with hot mixture. In the stage of mixing, the asphalt mixture was produced in a plant where discontinuous mixing was commonly employed. Batches of asphalt mixture were then transmitted to the truck. After material transportation to the construction site, construction machinery was deployed, including a paving machine, steel roller, and pneumatic roller. Loose asphalt mixture was then rolled and compacted.

SimaPro software was used to perform the LCA analysis. The midpoint impact category analyzed was Global Warm Potential (GWP). According to the IPCC GWP impact method, the corresponding GWP was calculated for the emitted GHG in kilograms of CO_2 equivalent (CO_2-eq). To aid in quantifying the energy consumption of each step, a tool was developed in MS Excel. The calculator used the data retrieved from the literature to estimate energy consumption and emission from the project.

2.2. Materials, Data Acquisition, and Calculation

Figure 1 shows the materials involved, related data resources, and the entire process in the system boundary. A typical asphalt pavement should include asphalt, aggregate, filler, and additives with a certain gradation. For the aim of the study, data acquisition for aggregate was of the most importance because the comparative study was initiated due to the change of basalt aggregate by BOF. It is noted that different sources represent different local conditions, technologies, and system boundaries. Aggregate production is therefore divided into the state of preparation, exploitation, and manufacturing. For the rest of the required data, such as basalt, limestone mining, and energy input including electricity for grill and coal, EcoInvent covered the entire database, including material transportation and material extraction [20]. As a comparative study was adopted, the energy consumption and emission data of asphalt [21,22], filler [23,24] and cement [25] in asphalt mixture were all from peer reviewed literature and published research reports. The emission factors for raw materials coming from China were favorable in data selection. For the equipment producing aggregate and paving asphalt mixtures, the energy consumption per kg was calculated as fuel consumption (L/h or kWh/h) multiplying working time (h) and conversion factor of fuel (e.g., MJ/L or MJ/kWh), and dividing by total mass (kg). The associated emission was calculated as energy consumption (MJ/kg), multiplying emission factors (e.g.,kg $_{CO2\text{-}eq}$/kg$_{energy}$) of various energy.

2.3. Scenario Analysis

Several viable scenarios were proposed based on a construction project. Table 1 shows the proportions of various materials in Asphalt-Treated Base (ATB) with a maximum 25 mm particle size for all scenarios. The baseline scenario used 10 t of cement as an anti-stripling agent, while all the other scenarios used no cement at all, which is ascribed to the good moisture resistance of the asphalt mixture with BOF. Note that the scenarios are based on the following conditions: the construction technology for using BOF is available under all scenarios, and the personnel involved in the asphalt and concrete pavements construction have identical skills.

Table 1. Proportions of the ATB-25 for all scenarios per lane for 1 km.

Scenario Ingredients		A Baseline	B Sunny Days	C Sunny Days	D Raining Days	E Raining Days
Transportation (km)		50	100	200	100	200
Coarse aggregate (kg)		787,000	907,000	897,000	907,000	897,000
Fine aggregate (kg)		180,000	302,000	352,000	302,000	352,000
Asphalt (kg)		38,000	40,300	42,000	40,300	42,000
Filler(kg)	Limestone powder	20,000	49,400	49,400	49,400	49,400
	Cement	10,000	0	0	0	0

Raw BOF should remain dry during the steps of crushing and sieving, otherwise the producing efficiency will fall considerably due to the jam in sieves. For crushed stones, the manufacturing capacity was 5 t/h according to the survey, as reflected in scenario A. However, it turned out to be 2 t/h for BOF aggregates due to the involvement of the sludge removal processor, taken into account in scenario B and C. It worsened to 1 t/h when the sludge was difficult to remove during rainy days, taken into account in scenario D and E. For an air exposed quarry, raining weather is the dominate interference condition that needs to be taken into consideration for scenario designing.

Transportation is also a sensitive element in LCA analysis, as previous discussion has revealed. In scenario B, BOF was used as a coarse aggregate in asphalt pavement. It is the most common approach for its utilization. In scenario C, both coarse and fine aggregate were replaced by BOF.

2.4. Uncertainty Analysis

Although the LCI of material extraction, transportation, and construction equipment were built in case study, the data uncertainty still exists when global evaluation is executed comparatively. The data uncertainty mainly comes from different sources of energy consumption for crushed stone, bitumen, and construction equipment in the calculation of energy consumption.

Monte Carlo simulation was performed to propagate the uncertainty factors into the life cycle energy consumption estimation by using the crystal ball add-in embedded in Excel. Numerical values of all the uncertainty factors were randomly sampled following their characterized distributions. In this study, the lognormal distribution, defined as the "probability distribution where the nature logarithm of the observed values that are normally distributed," was characterized by the variances of underlying normal distributions that describe the collected LCI input sample data from the literature. The inputs were delivered into the predefined LCA system to compute the corresponding energy consumption of single life stages and the whole life cycle. For the additional uncertainty, the pedigree matrix approach established by Weidema was used to quantify the Data Quality Indicators (DQIs). In the uncertainty analysis, basic uncertainty and additional uncertainty transferred from data quality indicators were both involved, as researchers suggested [19]. The energy consumption samples were obtained by applying 300,000 repetitions of the above computation process. Finally, the probability distributions of these samples can be estimated.

$$\sigma_t^2 = \sigma_b^2 + \sum_{i=1}^{5} \sigma_i^2$$

where σ_t^2 is the variance of the overall variance, σ_b^2 is the variance of the underlying normal distribution of basic uncertainties, σ_i^2 is the five additional uncertainties.

3. Life Cycle Inventory (LCI) Case Study in Inner Mongolia, China

3.1. LCI of Aggregate Production

The life cycle inventory of aggregate production was compiled according to field survey and personal communication. A typical extraction inventory for crushed stone and BOF is listed in Table 2. For the stages of preparation and exploitation, the exhausted energy per kg aggregate was calculated by the data acquired from the entire asphalt pavement project. The total fuel and materials exhausted were measured for 182,231 t aggregate used in a 20 km highway pavement in Inner Mongolia, China. The production of BOF aggregate has not been revealed in the literature. For the stage of manufacturing of crushed stone and BOF, the authors investigated a typical aggregate manufacturer. It consisted of high-pressure injection, vibrating sieves for sludge and dust removal, as well as a combination of a hammer crusher as a first breaker and an impact crusher as a second breaker. Figure 2 shows the structure of a processor for BOF production.

Table 2. Life cycle inventory for crushed stone and BOF aggregate.

Stages	Involved Equipment	Exhausted Energy Type	Energy Consumed per kg		Energy (MJ/kg)
			Diesel (L/kg)	Electricity (kwh/kg)	
State of preparation *	Bulldozer	Diesel	3.1×10^{-8}		7014.9
	Excavator	Diesel	1.7×10^{-4}		
	Dump truck	Diesel	1.9×10^{-8}		
	Excavator	Diesel	3.4×10^{-4}		
	Loader	Diesel	1.9×10^{-4}		
Stage of exploitation *	Electric air compressor	Electricity		7.2×10^{-5}	19,631.2
	Down-the-hole drill	Electricity		1.9×10^{-4}	
	Blasting equipment carrier	Diesel	3.8×10^{-8}		
	Dump truck	Diesel	6.0×10^{-6}		
	Sprinkler	Diesel	1.6×10^{-8}		
	Blasting	Ammonium nitrate explosive			
Stage of manufacture for crushed stones and BOF aggregate	Belt conveyer	Electricity		3.6×10^{-3}	16,173.1
	Electromagnetic iron remover*			3.2×10^{-4}	
	Hammer crusher			4.3×10^{-4}	
	Vibrating sieve			5.1×10^{-5}	
	Impact crusher			5.7×10^{-4}	
	Grab hopper*			1.0×10^{-4}	
	Pump*			2.1×10^{-4}	
Total (0.044 MJ/kg)					42,819.2

Note: the item with * is not needed for BOF aggregate production.

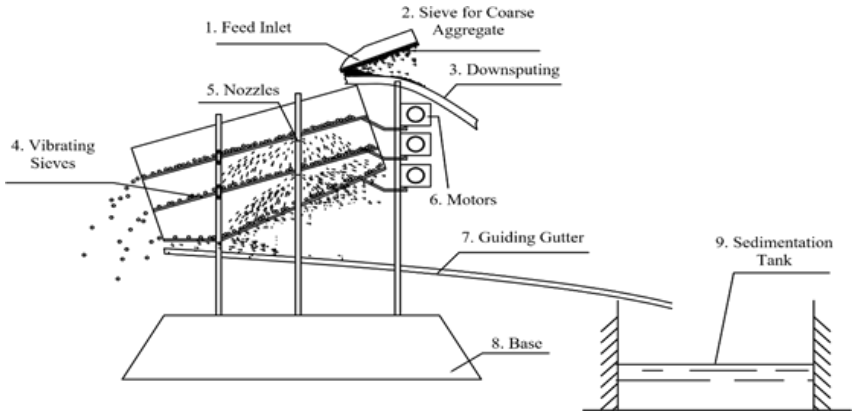


Figure 2. The industrialized processor for BOF aggregate [15].

3.2. LCI of the Mixing and Construction of Asphalt Mixture

Table 3 shows the LCI for mixing and construction of the asphalt mixture. Supplementary information for Table 3 was shown in Appendix A. A discontinuous mixing plant was employed in this case, with a capacity of 400 t hot asphalt mixture per hour. The process of mixing was appropriately simplified for calculation to heating and mixing. Heating is mainly designed for the removal of water as aggregate and temperatures increase. The aggregate, asphalt, and filler were all subjected to heating prior to mixing.

The road construction site required different types of equipment including pavers, rollers, and compactors for a new asphalt pavement. In order to compact the loose asphalt mixture to a dense state as soon as possible before it returned to an ambient temperature, a couple of rollers were deployed simultaneously. Each roller was responsible for one segment of hot pavement. In the mixing and construction phase, the energy consumptions were surveyed and calculated according to the capacity, power, and work hours of each piece of equipment.

Table 3. Life cycle inventory for mixing and construction of asphalt mixture.

Stages	Equipment	Number	Model	Exhausted Energy Type	Fuel Consumption (L/h)	Energy (MJ/kg)
Mixing	Heating drum	1	Tengsen TSM-4000	Coal	-	1.2×10^{-5}
	Plant	1		Electricity	-	7.2×10^{-3}
Paving	Paver	2	Vögele-2100	Diesel	25.9	
Compaction	Double steel roller	2	DYNAPAC-cc6200	Diesel	17.9	6.0×10^{-2}
	Steel roller	1	HAMM-HD138	Diesel	17.0	
	Pneumatic roller	2	XMG-XP303	Diesel	20.0	
	Pneumatic roller	1	XMG-XP262	Diesel	17.9	
	Double steel roller	1	BAOMAG-AD203	Diesel	4.2	

4. Life Cycle Impact Assessment

Life cycle impact assessment calculates and provides the environmental impact results of the functional unit based upon the earlier established LCI and the selected assessment method.

4.1. Global Warming Potential

The life cycle global warming potential (GWP) for all scenarios is shown in Figure 3. Compared to the baseline, scenarios B, C, and D all show a reduction in emission. The substitution of BOF as a coarse aggregate contributed greatly to the reduction of GWP, with a decrease of 12.79%. However, when the BOF processing worked on rainy days, it showed an increase by 2.09%, attributed to the reduction in production efficiency. The results also led to an unrevealed recognition that increased usage of BOF aggregates cannot reduce carbon emission when applied to the asphalt mixture when scenario B and C were compared. In fact, the asphalt mixture with both coarse and fine BOF aggregate consumed more energy in the whole life cycle except for the materials extraction phase, resulting in the increase in emission.

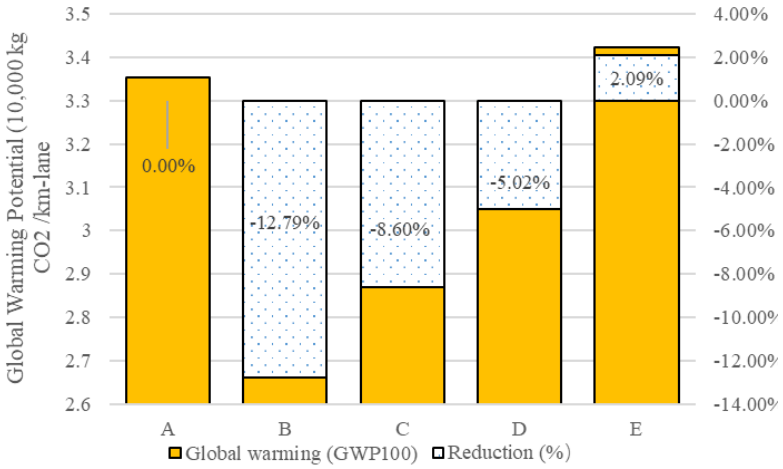


Figure 3. Global warming potential for all scenarios—no allocation.

The GWP for the best performing cases from each scenario was further investigated in detail to identify the impact reduction for each stage of the pavement. Figure 4 shows that the material extraction contribution to the total GWP impact for the baseline case (34 k-tons CO_2 eq.) was 70.9%. The contribution decreased to 50.1% when coarse and fine BOF aggregates were involved. Transportation, mixing, and construction caused 3.8%, 8.5% and 16.8% of the GWP emissions, respectively. As mentioned above, when more BOF aggregate was involved, its reduction effect was offset by the increase in fuel and resource consumption for the mixing, construction, and transportation phases, in particular.

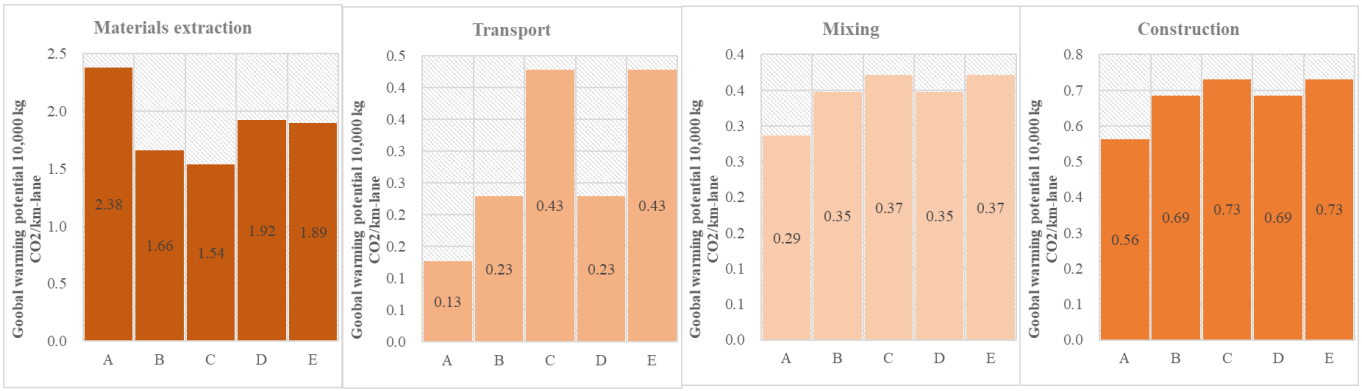


Figure 4. Breakdown of global warming potential for all stages.

4.2. Energy Consumption with Uncertainty Analysis

The cumulative energy consumptions for different scenarios are shown in Figure 5. The comparative study indicates that the case with only BOF aggregate produced on rainy days required the maximum energy. Transportation accounts for a certain portion, while the mixing and construction phases require almost the same energy. As for the baseline case, the energy consumption of material extraction was up to 156687 MJ for 1 km asphalt pavement per lane, compared to that of 17312.8 MJ of transportation. The mixing stage contributed the minimum energy consumption, while the material extraction phase accounted for the maximum.

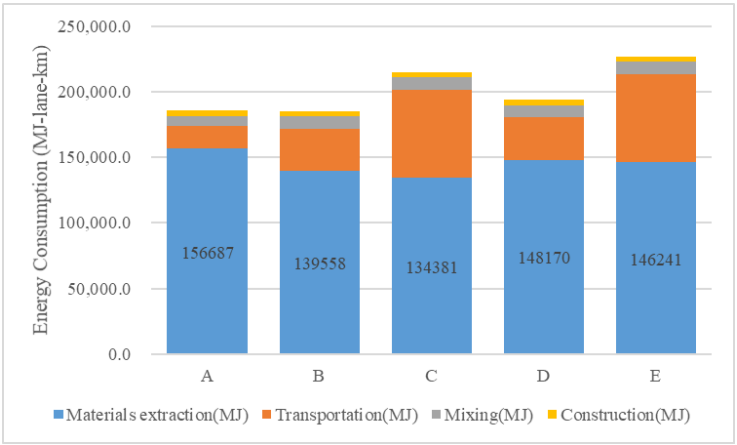


Figure 5. Energy consumption for different scenarios.

The breakdowns of energy consumption for different scenarios with uncertainty analysis in the life cycle of asphalt pavement are shown in Figure 6. The 5th, 25th, median, 75th, and 95th percentiles, as well as the maximum, the minimum, and the mean of the data, are indicated in the boxplots. The orange colors varying from dark to light in the plots distinguish the scenarios from A to E in turn. The fluctuation in energy consumption at the stage of material extraction was mainly attributed to the uncertainty of asphalt production. The uncertainty analysis for the mixing stage was not shown because it is assumed to be the same for all the scenarios. The order of magnitude of the energy consumption values were varied in different stages. Loss of BOF production efficiency in the inappropriate condition led to a significant increase in energy consumption.

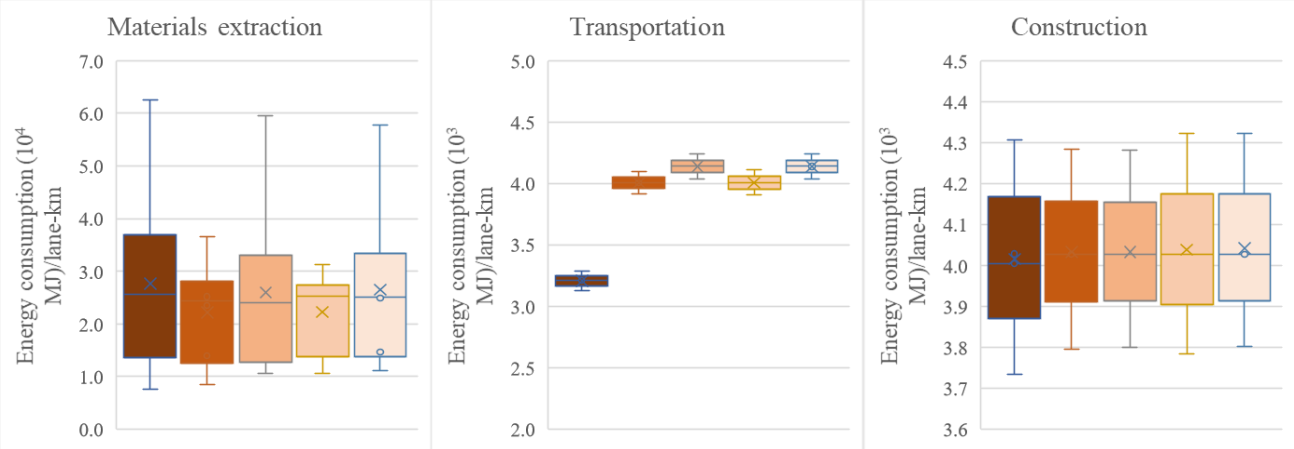


Figure 6. Breakdown of energy consumption with uncertainty analysis for different scenarios (The orange colors varying from dark to light in the plots distinguish the scenarios from A to E in turn).

4.3. Sensitivity Analysis of Transportation Distance

The above assessment indicates that the production efficiency of BOF aggregates and transportation both have effects on emission and energy consumption. At present, the availability of BOF aggregates mainly depends on metallurgical manufacturers in China. Almost all the work of preparation is completed by the manufacturers instead of contractors. Therefore, the utilization of BOF is considerably affected by cost-efficient transportation distances and the amount of usage in the asphalt mixture. The sensitivity analysis of transportation distance is shown in Figure 7.

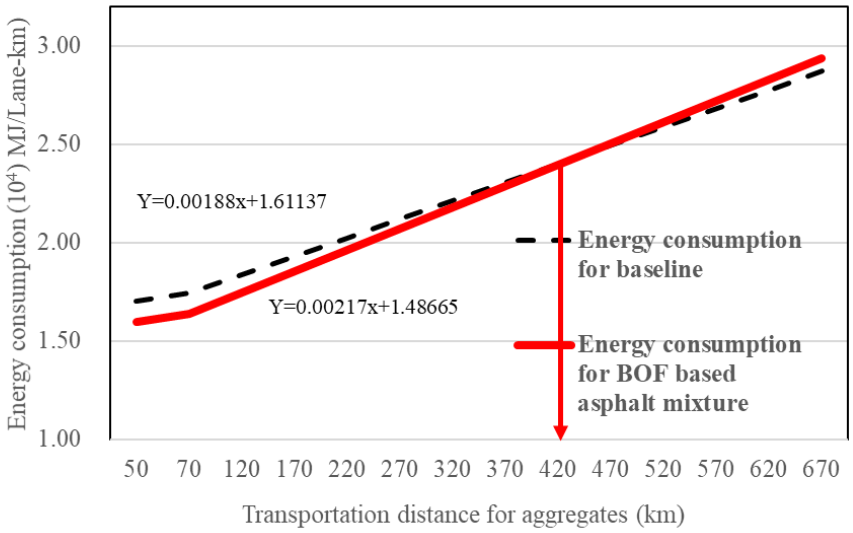


Figure 7. Sensitivity analysis of transportation distance on life cycle energy consumption.

Energy consumption of asphalt mixture is dominated by material extraction and transportation, as previous studies revealed. In the sensitivity analysis, the mixing and construction stages were neglected for their insignificant difference. When BOF aggregate is considered as the coarse aggregate in asphalt pavement, the economic aspect is assessed by the persons in charge of construction. Usually, the transportation distance is restricted within the range of 300 km for BOF aggregates. Otherwise, it becomes non-cost efficient. From Figure 6 it is shown that the energy consumption of BOF-based asphalt mixture remains lower compared to the baseline asphalt mixture until the transportation distance is up to approximately 430 km. The benefits of reduced energy consumption for BOF utilization are gradually offset by increased transport distances. Overall, the environmental

burden from transporting aggregates for longer distances is small compared to the total energy consumption from road construction. Therefore, the decision of BOF utilization is based on cost considerations.

5. Conclusions and Suggestions

The local life cycle inventory was built for the utilization of BOF in asphalt pavement via a case study. The energy required for crushed stone was determined to be 0.044 MJ/kg, which falls in the range of data from various LCA software and databases. By accounting for the properties of BOF aggregates, in terms of high porosity, dust content, producing condition, and transportation distance, the life cycle assessment of asphalt pavement with BOF was assessed by SimaPro with an uncertainty analysis.

The energy required for BOF production is within the range of results from the literature based on the local LCI. The pavements with BOF can reduce global warming potential (CO2-eq emission) up to 12% compared to ordinary pavement. The pavements with BOF can reduce up to 12% of emissions compared to ordinary pavement. The reduction of emission is mainly attributed to less energy consumption in the stage of aggregate production. Considerably more negative impacts of rainy weather on energy consumption of BOF than natural crushed stone can be concluded. Monte Carlo simulation indicated that the order of magnitudes of the energy values were varied, with materials extraction as the maximum contributor and transportation as the minimum contributor. The benefits of reduced energy consumption and emissions for BOF utilization are gradually offset by increased transport distances and the displacement of fine crushed stones, due to the increase in fuel and resource consumption for mixing, construction, and transportation stages.

Currently, the efficiency of BOF production largely depends on the capacity of sieving and dust removal. The production of BOF is recommended to occur in an enclosed space to eliminate the interruption of rain. The upper transportation limit is 430 km for BOF aggregates, according to the sensitivity analysis of the transportation distance. It seems that the decision of BOF utilization is appropriate by cost consideration. More manufacturers should be encouraged to participate in the production of BOF aggregates adjacent to other projects in order to reduce the impact of transportation on energy consumption and emissions.

In the current general scheme of BOF-based asphalt concrete, BOF as a coarse aggregate possesses the most significant effect on emission reduction. Although the reduction effect of asphalt mixture with both coarse and fine BOF aggregates is less considerable, BOF can be fully utilized instead of dumping. Therefore, it still worth promoting in China.

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Data Availability Statement: Some or all data, models, or code generated or used during this study.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Supplementary information for Table 3: Material production energy consumption, retrieved and rearranged from [17].

Inventory		Data Source	Pedigree Scores	DQI
Aggregate	0.0296	[26]	(3,4,1,5,2)	0.0066
	0.0866	[21]	(2,3,5,5,2)	0.0438
	0.0936	[27]	(2,3,4,4,2)	0.0104
	0.1990	[28]	(3,3,4,5,2)	0.0132
	0.0957	[29]	(3,2,4,4,2)	0.0107
	0.0530	[30]	(2,4,5,5,2)	0.0452
	0.0222	[31]	(3,4,5,5,2)	0.0526
	0.0740	[32]	(3,4,5,5,2)	0.0526
	0.0760	[33]	(3,4,5,5,2)	0.0526
	0.0382	[34]	(4,4,2,4,2)	0.0114
	0.044	Case study	(1,3,1,1,1)	0.025
Asphalt	3.7783	[26]	(3,4,1,5,2)	0.0066
	2.8900	[21]	(2,3,5,5,2)	0.0438
	5.3200	[27]	(2,3,4,4,2)	0.0104
	9.0000	[28]	(3,3,4,5,2)	0.0132
	10.5000	[29]	(3,2,4,4,2)	0.0113
	0.6300	[32]	(3,4,5,5,2)	0.0466
	0.4200	[30]	(2,4,5,5,2)	0.0452
	6.0000	[33]	(3,4,5,5,2)	0.0466
	1.3120	[34]	(4,4,2,4,2)	0.0114
Transport BOF and crushed stones	100	[26]	(4,2,1,5,2)	0.0107
	10	[35]	(2,4,3,5,2)	0.0072
	100	[35]	(2,4,3,5,2)	0.0072
	50	[36]	(2,4,2,5,2)	0.0054
	100	[34]	(4,4,2,4,2)	0.0114
	150	[26]	(4,2,1,5,2)	0.0107
Paving machine	30.00	[26]	(2,4,3,5,2)	0.0072
	15.10	[37]	(3,3,4,5,2)	0.0132
	18.10	[35]	(2,4,2,5,2)	0.0072
	20.00	[21]	(2,4,5,5,2)	0.0452
	22.00	[21]	(2,4,5,5,2)	0.0452
	26.62	[38]	(4,4,2,5,2)	0.0128
	40.13	[39]	(4,2,3,4,2)	0.0113
	25.88	Case study	(1,3,1,1,1)	0.025
Steel roller	30.67	[39]	(4,2,3,4,3)	0.0187
	12.00	[21]	(2,4,5,5,3)	0.0526
	18.00	[21]	(2,4,5,5,3)	0.0526
	17.00	[37]	(3,3,4,5,2)	0.0132
	17.00	[26]	(2,4,3,5,3)	0.0128
	12.85	[35]	(2,4,2,5,3)	0.0146
	17.91	Case study	(1,3,1,1,1)	0.025
	17.01	Case study	(1,3,1,1,1)	0.025
	4.20	Case study	(1,3,1,1,1)	0.025
Pneumatic roller	18.55	[39]	(4,2,3,4,3)	0.0187
	12.00	[21]	(2,4,5,5,3)	0.0526
	18.00	[21]	(2,4,5,5,3)	0.0526
	17.00	[37]	(3,3,4,5,2)	0.0132
	17.00	[26]	(2,4,3,5,3)	0.0128
	12.85	[35]	(2,4,2,5,3)	0.0146
	20.00	Case study	(1,3,1,1,1)	0.025
	17.91	Case study	(1,3,1,1,1)	0.025

Table A2. Summary of uncertainty factors.

Uncertainty Factors	Variables	Uncertainty Distribution Type	Parameters	
			μ	σ
Material production energy consumption (MJ/kg)	Aggregate	Lognormal	−2.7828	0.624
	Asphalt	Lognormal	1.0383	1.151
Mixing	-	-	-	-
Transportation distance (km)	Transport BOF aggregate	Lognormal	4.6052	0.693
Energy consumption of construction equipment (L/h)	Paver	Lognormal	3.1657	0.311
	Steel roller	Lognormal	2.6858	0.539
	Pneumatic roller	Lognormal	2.7996	0.186

Note: "-" represents data that were unavailable.

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