

Article

Carbon Accounting for Permeable Pavement Based on the Full Life Cycle Approach and Its Application

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Abstract: Conventional pavement in aging communities requires renovation in alignment with global carbon reduction initiatives. This study, centered on upgrading facilities in Guangdong, Hong Kong, and the Macao Greater Bay Area (GBA), utilized the Energy Expert platform to assess the carbon footprint of permeable pavement using life cycle assessment (LCA). The results revealed that the total carbon emission of the 64,065 m² permeable pavement was 7066.21 tCO₂eq. The carbon emission contribution, from highest to lowest, was the production phase, maintenance phase, end-of-life phase, and construction phase. Notably, transportation alone constituted a substantial portion, amounting to 30.15% of total carbon emissions. Compared to traditional pavements, permeable pavement showcased substantial potential for carbon reduction, primarily during the use phase, by enhancing groundwater recharge and mitigating the urban heat island effect, which is critical in reducing the carbon footprint. The estimated total carbon reduction was 853.10 tCO₂eq. Sensitivity analysis highlighted diesel energy use in the maintenance phase (51.20%), transportation of cement raw materials in the production phase (45.80%), and transportation of graded gravel for disposal in the end-of-life phase (3.00%) as key factors. Our findings suggest that adopting specific carbon reduction measures, such as substituting gangue for cement binder, transitioning to manual sweeping, and recycling all discarded materials can achieve notable reductions in the respective phases. These findings contribute to a deeper understanding of the role of permeable pavement in reducing carbon emissions, providing insights for the renovation of aging communities.

Keywords: permeable pavement; life cycle assessment; carbon footprint; carbon reduction; aging community renovation



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1. Introduction

Reducing carbon emissions is now widely agreed upon. As the largest carbon emission emitter, China has also unequivocally pledged to achieve “carbon peaking” and “carbon neutrality” [1,2]. Cities are the main sources of carbon emissions [3–5]; this is particularly evident in aging communities [6], where conventional pavement predominates. In addition to having very significant carbon emissions, these pavements are also not very permeable [7–9], which makes them vulnerable to urban flooding [10]. This can negatively impact surface ecology [11] and exacerbate the urban heat island effect [12]. In light of international efforts to reduce carbon emissions [13,14], it is vital that aging communities undergo renovations as soon as possible. Renovating pavements in aging communities offers a promising avenue for urban carbon reduction. Converting them to permeable pavement is a sustainable solution [15–17]. A typical permeable pavement structure comprises a top layer, a bedding layer, and a base layer [18]. The top layer must be permeable and compression resistant. Sand, gravel, and crushed stone make up the majority of bedding and sub-base materials; they provide soil insulation, permeability, and support. The specific structural design facilitates matter, water,

and heat exchange, offering several benefits. These benefits include absorbing pollutants from infiltrating water [19–22], reducing surface runoff [23–26], mitigating the urban heat island effect [27], and changing pavement albedo [28,29].

LCA is one of the most common and effective methods [30] used in carbon accounting studies for permeable pavement. It can quantitatively analyze both direct carbon emissions during the pavement process, such as energy consumption during use, and indirect carbon emissions, including those associated with material transport and equipment use [31]. Several studies have highlighted the significant reduction in carbon emissions during the permeable pavement and use phases by comparing the LCA results of permeable pavement with those of conventional asphalt and concrete pavement [32]. With proper design and maintenance, permeable pavement can effectively reduce long-term environmental burdens. Further research has also explored the use of alternative materials, such as industrial by-products or recycled materials in permeable pavement, which not only reduce initial carbon emissions, but also enhance the overall environmental performance of the pavement. With proper design and maintenance, permeable pavement can effectively reduce long-term environmental burdens. Recent research demonstrates that permeable pavement offers ecological and carbon reduction benefits during the usage phase [33–36]. However, studies also indicate that the carbon reduction benefits of permeable pavement in other phases are not significant [37]. While the carbon reduction benefits during the usage phase are noteworthy, they alone do not substantiate permeable pavement as a full life-cycle substitute for conventional pavement. Consequently, it is essential to conduct a thorough evaluation of its carbon footprint across the full life cycle. In addition, the sustainability and carbon reduction potential of permeable pavement necessitates a comprehensive evaluation and enhancement by weighing the benefits of the usage phase against the environmental impacts of the production and construction phases [38]. These details consider enhancement options at each phase from a holistic life-cycle perspective.

With an emphasis on the renovation of aging communities, this study offers a comprehensive carbon footprint analysis of permeable pavement across its full life cycle, providing insights that go beyond the existing literature, which often focuses on specific phases [30]. Guanggang Park in the Greater Bay Area (GBA) was employed as a case study. Most of the existing studies focus on the qualitative study of the environmental benefits of permeable pavement, but this study quantifies the specific emission reduction benefits of permeable pavement in the use phase through the LCA method [25,39]. Utilizing the carbon emission factor database and the Energy Expert platform, the carbon emissions across each life-cycle phase of permeable pavement were meticulously analyzed. These emissions were then compared with the carbon reduction benefits observed during the usage phase. The comparison research provided empirical support for the potential of permeable pavement to displace conventional pavement, in addition to theoretical insights. Moreover, it offered significant backing for the renovation of pavements in aging communities within the GBA. In addition, through sensitivity analysis, this study evaluated the factors contributing to each phase of the LCA carbon footprint life cycle of permeable pavement. Optimization suggestions were derived to enhance the applicability of permeable pavement across each phase, facilitating its low-carbon application in practical scenarios.

2. Materials and Methods

2.1. Study Area

This study focused on the carbon accounting of permeable pavement within aging communities in the GBA. Adopting a full life-cycle approach, the study centered on the transformation of Guanggang Park in Guangzhou. This park, situated within Guanggang New District, was formerly an abandoned steel-making industrial zone [40]. Encompassing a total area of 298,000 m², the project embraced a design ethos that respects the original site characteristics while retaining existing facilities.

2.2. Research Scope and Boundary

The total area of permeable pavement was 64,065 m². The objective was to evaluate permeable pavement's carbon emissions in all aspects of its life cycle, from cradle to grave, including material manufacture, construction, usage and maintenance, end-of-life, and transportation. The service life of permeable pavement in this study was determined to be 11.3 years, drawing from relevant existing studies (Table S1).

With the entire system boundary, the functional unit was defined as “64,065 m² permeable pavement, ‘11.3 years’ full life cycle”, as shown in Figure 1. In accordance with the standard approach in LCA research, manpower is excluded from the system boundary [41]. Furthermore, the pre-pavement of roads may induce traffic impacts [42]. However, because Guanggang Park was renovated from an abandoned steel factory, it has no impact on traffic. Numerous studies have indicated that permeable pavement generates carbon emissions due to rolling resistance during the usage phase [43–46]. However, the carbon emissions from this aspect were not taken into account in this study because the permeable pavement at Guanggang Park is mostly used for pedestrian walkways and has little to do with the rolling resistance of automobiles. Furthermore, Wang provided a unique calculation model [33] and showed that permeable pavement demonstrates absorption properties for pollutants in infiltrating water. However, the present study did not establish a clear relationship between pollutant removal and carbon reduction. Consequently, this aspect was not included within the system boundary of this study.

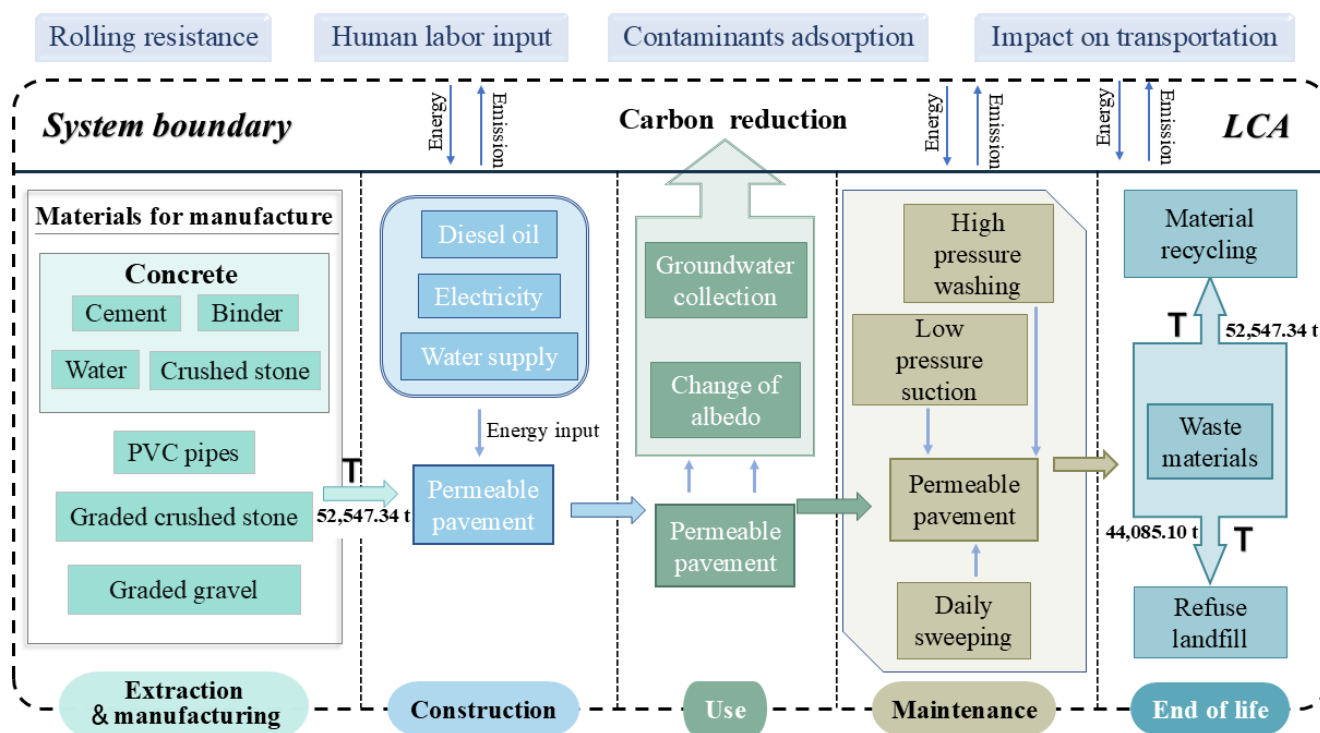


Figure 1. System boundary settings for the LCA of permeable pavement.

2.3. Structure of Permeable Pavement

Surface layers, bedding layers, and grass-root levels make up the structure of permeable pavement, and each is essential to its operation. Permeable pavement structural design takes into account a number of aspects, such as pavement location and usage [47]. Guangzhou City is characterized by a maritime subtropical monsoon climate with substantial annual precipitation, placing pressure on road surface drainage within Guanggang Park. Therefore, the choice of suitable permeable surface layer materials is imperative. Compressive strength and material sustainability are crucial factors to take into account, given Guanggang Park's aesthetic and load-bearing requirements. Because of its performance

qualities and adaptability, permeable concrete is the best material for surface layers [48–50]. Permeable concrete offers high water permeability coefficients [51,52] and efficient heat dissipation capabilities [8,52,53]. P.O42.5 cement, a general-purpose permeable concrete binder, and crushed stone meeting the requirements of GB/T 1468 [54] for construction pebbles and crushed stone, the secondary standard, were used in this study. Water was provided on-site through a piped water supply. In addition to surface materials, the base and bedding materials must also facilitate permeability to allow rainwater infiltration and groundwater recharge or recycling through drains [55,56]. Material details for permeable concrete in each layer are shown in Table 1 and Figure 2.

Table 1. Material information for each layer of permeable concrete.

Material (Layer)	Thickness (mm)/ Length (m)	Density (kg/m ³)	Weight (kg)
Cement (top layer)	N/A *	2.88×10^3	1.95×10^6
Water (top layer)	N/A	1.00×10^3	7.33×10^5
Cementitious material (top layer)	N/A	N/A	8.20×10^3
Gravel (topping)	N/A	2.10×10^3	8.46×10^6
Grading gravel (bedding)	150	2.10×10^3	2.02×10^7
Graded gravel (base layer)	150	2.20×10^3	2.11×10^7
PVC drainage pipe	1.49×10^3	1.40×10^3	6.36×10^3

* The top layer comprises a mixture of various materials, thus no specific thickness value is available, expressed as N/A.

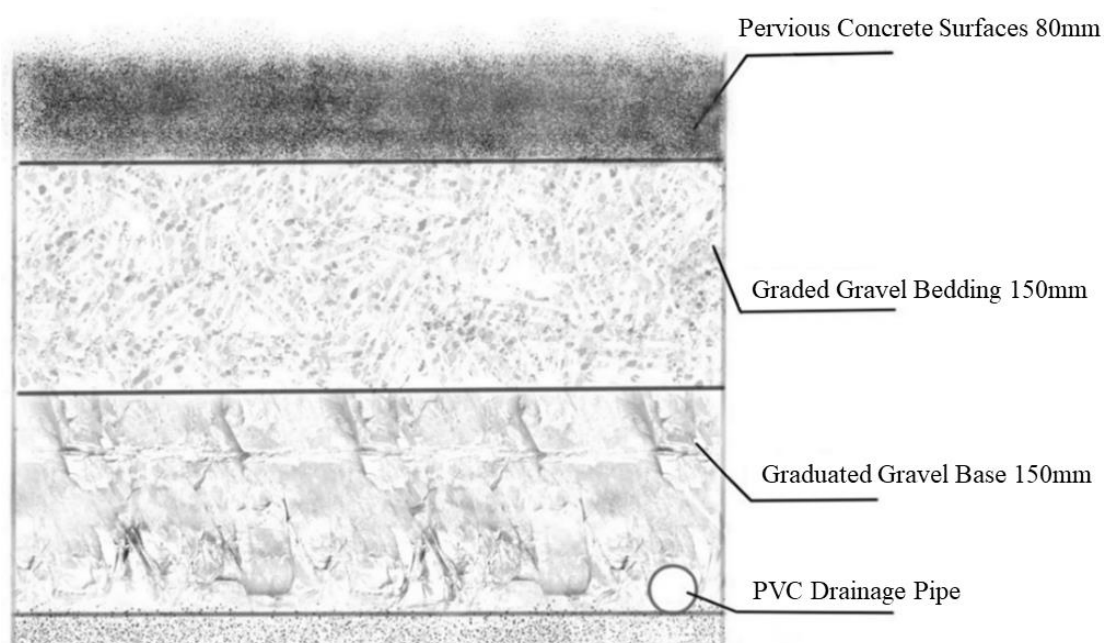


Figure 2. The design of permeable pavement structure (self-drawn by the author).

2.4. Life Cycle Carbon Inventory Analysis

2.4.1. Full Life Cycle Approach and Reference Standards

LCA is one of the best tools to assess environmental impacts [6,57]. The 1993 international standard provided a framework for LCA assessment based on environmental management standards. ISO 14040 [58] establishes the fundamental principles and frameworks for LCA implementation, while ISO 14044 [59] defines the requirements and guidelines for LCA according to ISO standards [40,60]. These standards delineate an LCA framework comprising four phases: objective and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation [61]. To determine input processes, inventory analysis mostly relies on data from databases, websites, literature, and

other sources [62,63]. Energy Expert platform modeling and data importation were used in this study to acquire data, making it easier to analyze carbon emissions at every phase of the full life cycle.

2.4.2. Production Phase

During the production phase, inventory assessments evaluated the carbon emissions of the materials by focusing on their features. When choosing materials for the permeable pavement layers, prior research findings and particular needs were taken into account. This study selected permeable concrete as the surface layer material, opting for graded gravel with superior water permeability as the bedding material. Moreover, graded gravel, along with graded sand and gravel, were chosen as subgrade materials, facilitating rainwater infiltration through the pavement to replenish groundwater or to be recycled through the drainpipe. The best cement, gravel, adhesive, and water mix ratio for a permeable concrete surface layer was found to be 380:1650:16:143 (kg/m³) in this study. Table S2 presents all carbon emission factors utilized in this study, sourced from the Energy Expert platform.

2.4.3. Transportation Phase

The carbon emissions produced during the transportation of production-related items from the suppliers to Guanggang Park were the main focus of the inventory analysis during the transportation phase. This study opted to analyze the suppliers closest to Guanggang Park. Notably, the water required for manufacturing permeable concrete was directly sourced from water pipes laid within the construction site of Guanggang Park. However, energy consumption during water supply must still be considered. Using information from the Energy Expert platform, this study chose suitable modes of transportation based on the total mass of materials and transportation distances in order to calculate the carbon emissions components. Table S3 displays the manufacturing materials' transportation distances.

2.4.4. Construction Phase

The engineering procedures that potentially result in carbon emissions, such as the usage of mechanical equipment and wastewater treatment after construction, were included in the inventory analysis of the construction phase. The energy consumption during the construction phase in Guanggang Park was 3619.67 t of water supply, 3574.83 kW·h of electricity, and 30,474.44 kg of diesel fuel. Throughout the construction phase, a portion of the water supply transformed into wastewater, which meant that the carbon emissions from treating it had to be taken into account. The estimated volume of wastewater generated during construction was 766.92 t, using the permeable pavement area as a reference. In this study, construction wastewater underwent direct transportation to the Hunt Wastewater Treatment Plant through a sewage pipeline. Notably, pipeline transportation-related carbon emissions were not taken into account. By integrating the modified A2/O process employed at the plant for wastewater treatment, corresponding carbon emission factors sourced from the Energy Expert platform were identified and utilized for carbon accounting.

2.4.5. Maintenance Phase

The inventory analysis during the maintenance phase primarily focused on the carbon emissions generated throughout the maintenance process within the pavement's life cycle. The individual maintenance for permeable pavement typically included sweeping, high-pressure air flushing, high-pressure water washing, and low-pressure pumping [64–67]. But where possible, combining maintenance strategies worked better [68]. In order to preserve the permeable pavement in Guanggang Park, a mix of high-pressure flushing, low-pressure suction, and daily cleaning was used in this study. The consumption of diesel, water, and electricity during the maintenance of the permeable pavement in Guanggang Park was estimated at 482,623.00 kg, 398,163,975.00 m³, and 330,163.94 kW·h, respectively, based on the proportion of service life.

2.4.6. End-of-Life Phase

The inventory analysis conducted during the end-of-life phase of permeable pavement primarily looked at the operational procedures that could lead to waste material-related carbon emissions, such as recycling, waste transportation, demolition, and related activities. The dismantling process alone accounted for 90% of the energy consumption during the construction phase [69], necessitating 3257.71 t of water supply, 3217.34 kWne of electricity, and 27,427.00 kg of diesel fuel, equivalent to a carbon emission of 108.98 tCO₂eq. In theory, all the materials were disposed of during the construction process. However, different materials require different disposal techniques due to their unique properties. Each material layer was moved to the proper locations for final disposal [70]. This study aligned the actual disposal of engineering materials with the inclusion of carbon emission factors from the Energy Expert platform. It was found that materials such as crushed stone and PVC water pipes were recycled, while others were discarded or landfilled. The procedure for treating wastewater was the same as that seen during the construction phase [69]. Table S4 provides comprehensive details about the material transportation process during the end-of-life phase.

2.5. Energy Expert Platform

The Energy Expert platform, developed by Alibaba Cloud, serves as an advanced hub for carbon and energy management services. This platform integrates various databases, including Ecoinvent, the Intergovernmental Panel on Climate Change (IPCC), the European Reference Life-Cycle Database (ELCD), and the China Products Carbon Footprint Factors Database (CPCD), leveraging artificial intelligence and big data analysis. It provides users with features like carbon footprint accounting, data quality evaluation, uncertainty analysis, and sensitivity analysis. This study utilized the Energy Expert platform for carbon accounting to facilitate data importation, modeling, and analysis of the full life cycle of permeable pavement. It oversaw the data on carbon emissions at each phase, making it easier to analyze and interpret the study's findings thoroughly.

2.6. Carbon Reduction Benefits

2.6.1. Carbon Reduction Benefits of Water Recycling

Permeable pavement serves as a mechanism for rainwater collection adsorption and purification, thereby facilitating groundwater recharge [71,72]. This recycled groundwater incrementally offsets the carbon emissions associated with using pumps to extract equivalent groundwater volumes. In Xixian New District, Xi'an City, Shaanxi Province, Liu constructed a 1000 m² functional unit with the capacity to collect 338.00 t of water yearly [73]. Equation (1) provides the formula for determining the amount of recycled water from permeable pavement [33].

$$V = P \times (1 - \varphi) \times A \times \sigma \quad (1)$$

where V represents the volume of recycled water (m³), P is the annual precipitation (mm), φ stands for the runoff coefficient of the pavement, typically ranging between 0.1 and 0.6, with a value of 0.3 chosen for this study, A is the area of pavement (m²), and σ is the unit coordination coefficient.

2.6.2. Carbon Reduction Benefits of Mitigating the Urban Heat Island Effect

The variation of surface albedo influences the radiative forcing (RF), which is quantified as the rate of energy change per unit area. Compared to conventional impermeable pavements, permeable pavement can increase the pavement's albedo, alter the pavement's radiation characteristics, mitigate the urban heat island effect, and consequently reduce carbon emissions [74]. Through modeling, the carbon reduction contributed by changes in pavement albedo was quantified. Monte Carlo simulation was used as a supplement to

show the results' uncertainty. Equation (2) illustrates the formula connecting the change in albedo per unit area of pavement to carbon reduction.

$$+0.01\alpha = \frac{1.087 \times \text{RF} \times t}{0.217 \times t - 44.78 \times e^{-t/172.9} - 0.22 \times e^{-t/1.186} + 51.26} [\text{kgCO}_2] \quad (2)$$

where α is the albedo of permeable pavement, the RF reference range is 1.12~2.14 (W/m^2), used as 1.54 in this study, and t is the pavement service life (year).

2.7. Inventory and Results Uncertainty Analysis

Uncertainty in LCA is inevitable owing to various factors, such as data quality, modeling techniques, and methodology. [75]. Studies have indicated that higher data quality corresponds to lower uncertainty levels [76,77]. Therefore, the overall uncertainty in the LCA process can be reduced by improving the data quality for inventory items with high uncertainty. Evaluating data quality involves constructing a spectral matrix based on input data, enabling the quantitative presentation of confidence levels, temporal aspects, and geographical representations of the data [78]. This study focused on enhancing data quality through the use of the Energy Expert platform and the data quality indicator (DQI) method of computation [79].

2.8. Sensitivity Analysis

Using the Energy Expert platform, sensitivity analyses of each carbon emission inventory item in the LCA of permeable pavement were conducted individually. This study investigated appropriate carbon reduction optimization options for each step and identified several extremely sensitive inventory items for in-depth analysis. For validation, this study also included a comparison of carbon emissions before and after carbon reduction measures were put in place, along with the findings of the sensitivity analysis. The sensitivity analysis can provide theoretical guidance for implementing green energy-saving and emission-reduction measures in future permeable pavement applications.

3. Results

3.1. Uncertainty Analysis of LCA Results

Figure S1 shows that LCA carbon emission accounting showed an overall uncertainty of 5.82% based on model calculations. The most uncertain inventory items identified were diesel use during the maintenance phase, and cement and crushed stone in the production phase. In the maintenance phase, a suitable alternative carbon emission factor for diesel use was not found, thus precluding the optimization replacement for this data segment. After remodeling, the overall uncertainty dropped to 5.70%, with reductions of 18.14% and 42.90%, respectively, in the cement and crushed stone production phases. This demonstrates that enhancing data quality can mitigate the overall uncertainty associated with LCA carbon emissions accounting. The data quality evaluation is shown in Figure S2.

3.2. Carbon Footprint Accounting Results

The production phase, which includes transportation, emerged as a substantial contributor, accounting for 47.05% of the total carbon emissions, as illustrated in Figure 3a. This phase encompassed the production processes of raw materials and their transportation to Guanggang Park. Close behind, the maintenance phase came in second place, with 26.56% of the total carbon emissions. Of these emissions during this phase, 99.24% were primarily attributable to the use of diesel fuel. The end-of-life phase exhibited the third-highest carbon emission contribution, equivalent to 24.67% of the total emissions. Primary carbon emissions within this phase stemmed from the pavement material stacking and disposal process, accounting for 80.69% of total emissions, with recycling and energy consumption in the dismantling process contributing 13.06% and 6.25%, respectively. As illustrated in Figure 3b, transportation accounted for 30.15% of carbon emissions, energy consumption for 29.84%, and the production and disposal of raw materials for 40.01% of

emissions. Analyzing the contribution of carbon emissions across all raw materials and energy items listed in the inventory (Figure 3c), it was determined that diesel fuel usage in the maintenance phase emerged as the highest contributor to the overall product carbon footprint, constituting 26.09%. Cement production in the production phase followed closely, accounting for 25.80%, while crushed stone production in the production phase accounted for 11.18%.

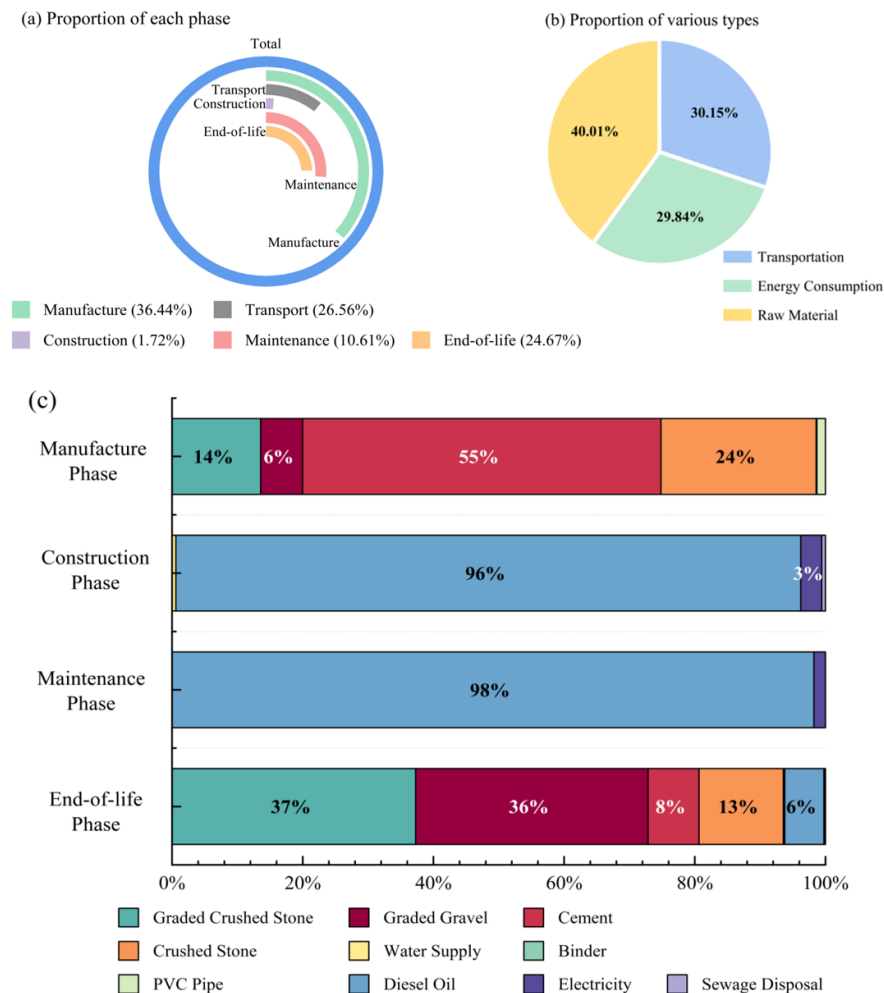


Figure 3. Permeable pavement LCA carbon emission inventory contribution. (a) Carbon emission contribution for each phase of permeable pavement; (b) Carbon emission contribution for various types of permeable pavement; (c) Carbon emission contribution of permeable pavement LCA list items in their phases.

3.3. Carbon Reduction Benefits

In this study, carbon reduction resulted in the usage phase, which comprised two components. The first component involved the carbon reduction attributed to groundwater collection by the permeable pavement. Based on the CEIC database for 2020, the annual precipitation in Guangzhou reached an average of 1890.30 mm. The estimated average rainfall collection is 73,317.87 t/year, considering an 11.3-year service life, culminating in a total of 828,492 m³ over the life cycle. The carbon emission factor for groundwater pumping, according to the Energy Expert platform, showed that 1 m³ of groundwater extraction produced 0.68 kg of carbon dioxide emissions. As a result, the water resources recovered in this study by using permeable pavement are equivalent to mitigating a 563.37 tCO₂eq carbon footprint. The second component pertained to the carbon reduction achieved by permeable pavement compared to conventional pavement, factoring in changes in pavement albedo. Drawing from prior research, it was determined that permeable pavement reduced

carbon emissions by 4.5 tCO₂eq per unit area. Considering the cumulative findings from prior studies, the carbon emission reduction attributed to permeable pavement amounted to 4.56 kgCO₂eq. The total emission reduction reached 289,730.10 tCO₂eq, equivalent to approximately 289.73 tCO₂eq. The combined carbon reduction from both components totaled 853.10 tCO₂eq. Based on this study, the area set for permeable pavement in Guanggang Park is 64,065 m², so the unit carbon reduction is 13.32 kg CO₂eq/m². The net emissions over the lifecycle amounted to 6213.07 tCO₂eq, with the reduction in carbon emissions during the usage phase constituting 12.07% of the total emissions (Figure 4).

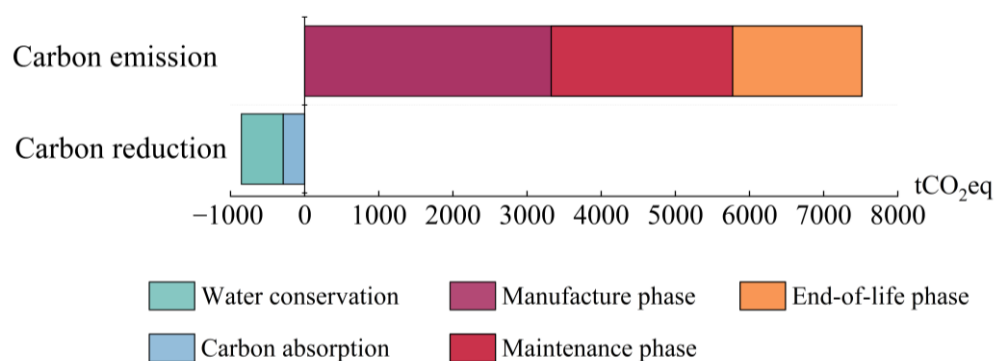


Figure 4. Carbon reduction benefits of permeable pavement.

The carbon reduction benefits of permeable pavement in this study were not sufficiently noteworthy. On the one hand, this is because there may be some deviations in the existing measurement methods for carbon reduction benefits. On the other hand, several benefits of reducing carbon emissions that are currently difficult to measure—such as the adsorption of pollutants and the decrease of carbon emissions through moderating the urban heat island effect—were left out of this study. Among these, pollutant adsorption can reduce carbon emissions during the purification of infiltrated water, while alleviating the urban heat island effect can translate into carbon reduction benefits.

3.4. Sensitivity and Scenario Analysis Results

3.4.1. Sensitivity Analysis Results

In the sensitivity analysis results of this study (Figure S3), the highest sensitivity was observed in diesel energy usage during the maintenance phase (51.20%), followed by the production and transportation of cement raw materials in the production phase (45.80%), and the transportation of graded gravel during waste stacking in the end-of-life phase (3.00%). These results emphasized how crucial it is to develop better alternatives for waste disposal and raw material production as well as to optimize the maintenance approach for permeable pavement.

3.4.2. Carbon Reduction Measures Analysis

This study analyzed the phases corresponding to the three most sensitive list items in permeable pavement. After adopting the carbon reduction measures, we reevaluated the LCA modeling to determine their impact on the final efficacy and results. We also investigated carbon reduction methods for these high-sensitivity items and examined the viability of quantifying these measures within LCA.

The carbon emissions of highways are mainly produced during the material production phase [80]. In the cement production phase, this study considered the addition of coal gangue [81,82]. Additionally, fly ash was taken into consideration as a substitute material [24,83]. The ideal mix ratio for permeable concrete with substitute materials was established by carefully taking into account variables such as the permeability coefficient and the compressive strength of the road surface (Tables S5 and S6). Subsequently, the updated data were reentered into the Energy Expert platform for modeling and accounting, followed by a sensitivity analysis. Figure 5a illustrates the carbon reduction resulting

from the two different material substitution methods. Incorporating coal gangue, the total carbon emissions amounted to 2397.81 tCO₂eq, which represents a significant reduction of 27.88% when compared to the initial setting. The carbon emissions from cement production decreased from 1823.42 tCO₂eq to 965.57 tCO₂eq, reducing them by 47.05%. In the cement sensitivity analysis, the sensitivity shared decreased to 27.10%.

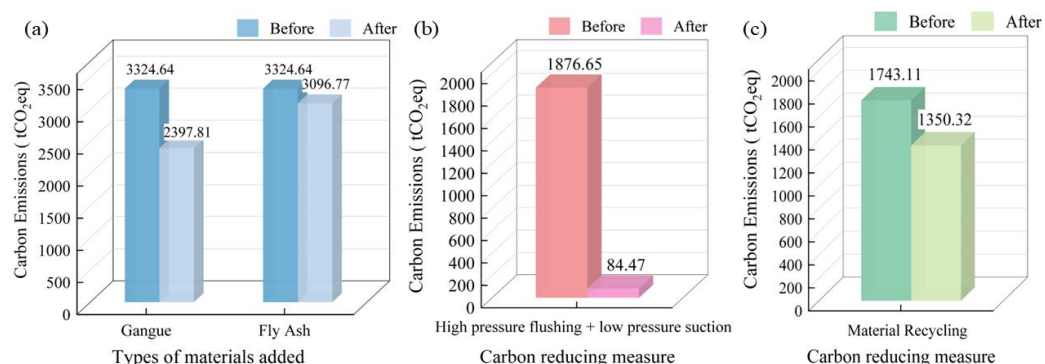


Figure 5. Comparison of carbon emissions before and after different carbon reduction measures. (a) Replace raw materials with fly ash and coal gangue, respectively, in the production phase; (b) Adopt the maintenance method of high-pressure washing combined with low-pressure suction in the maintenance phase; (c) Recycle materials in the end-of-life phase.

For diesel energy use during the maintenance phase, combined maintenance is superior. Energy consumptions for various maintenance method combinations in the maintenance phase are shown in Table S7. This study primarily considered adopting high-pressure flushing combined with low-pressure suction for the maintenance of permeable pavement while replacing mechanical sweeping with manual sweeping. The overall carbon emissions in the maintenance phase were 84.47 tCO₂eq, which was 95.50% after entering the updated data into the Energy Expert platform and recalculating. This was 95.50% less than the total carbon emissions from the original reference, indicating a significant reduction in carbon emissions (Figure 5b).

Given the complexity of carbon reduction measures during transportation, we prioritized altering the waste material disposal method to fulfill carbon reduction goals. In this study, we shifted from landfill to recycling for waste material disposal. The overall carbon emissions during the end-of-life phase dropped by 22.53% to 1350.32 tCO₂eq after being recalculated by remodeling (Figure 5c). Moreover, the proportion of carbon emissions dropped from 24.67% to 20.23%. Of this reduction, 121.70 tCO₂eq was attributed to the change in disposal method, while the remainder was due to the change in the transportation endpoint from the original landfill to the recycling company.

In the production, maintenance, and end-of-life phases, the reductions in carbon emissions (Figure 6a) and percentages (Figure 6b) of reduction, from highest to lowest, were the maintenance phase, the production phase with coal gangue replacing cement, the end-of-life phase, and the production phase with fly ash replacing cement. As a result, in the event that permeable pavement is unable to reduce emissions in all phases at the same time, the study's findings about effectiveness should be taken into consideration while prioritizing carbon reduction strategies. When it comes to implementing carbon reduction measures, the maintenance phase should take precedence, with the use of fly ash in the production phase being considered as a last resort.

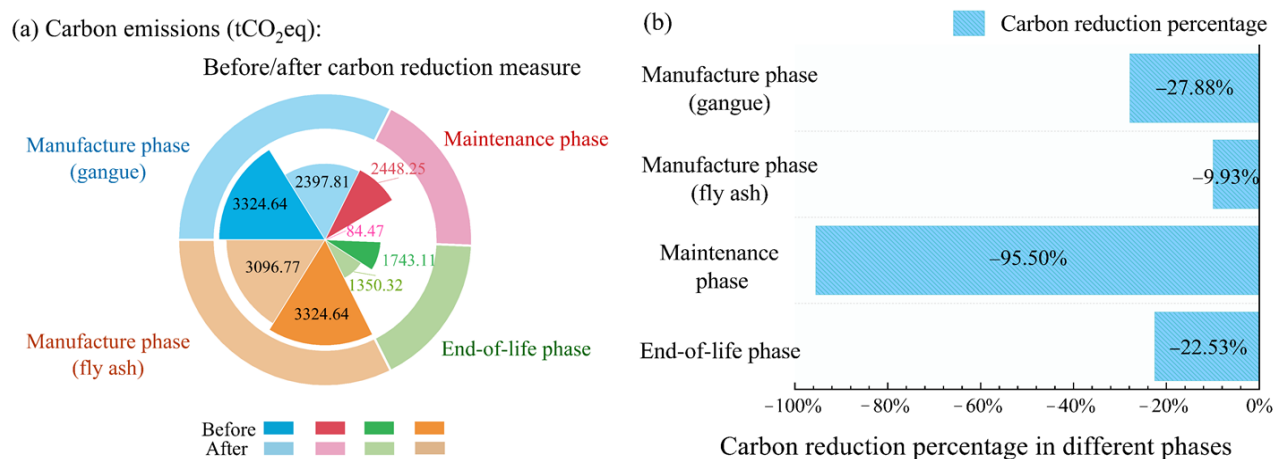


Figure 6. Comparison of carbon reduction effects among manufacture, maintenance, and end-of-life phases. **(a)** Direct comparison of carbon reductions in each phase; **(b)** Comparison of carbon reduction percentages in each phase.

3.4.3. Integrated Optimization Simulation Analysis

This study delved into a comprehensive carbon reduction optimization simulation. The three phases' best carbon reduction plans were taken into account and included in the model for computation. As illustrated in Figure 7, within this comprehensive carbon reduction optimization simulation, the total carbon emissions throughout the permeable pavement life cycle amounted to a mere 3136.30 tCO₂eq, reflecting a reduction of 55.62%. Remarkably, the carbon reduction effect achieved after the implementation of all the measures was approximately 4.61 times greater than the reduction of 853.10 t CO₂eq observed during the usage phase.

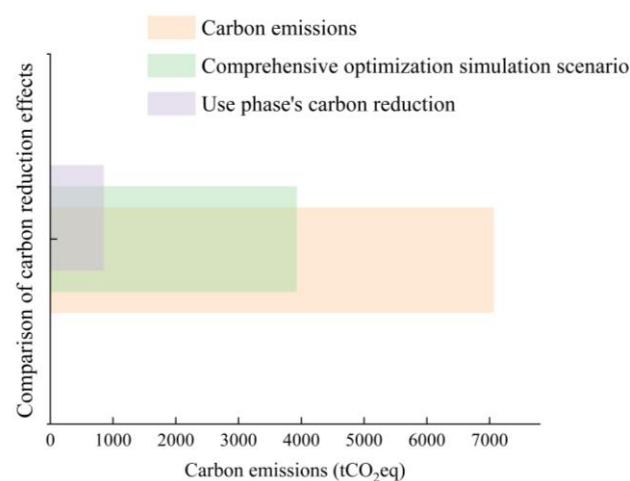


Figure 7. Comparison of comprehensive optimization simulation and use-phase carbon reduction.

4. Conclusions

This study evaluated the carbon emission reduction benefits of permeable pavement using the LCA method throughout its lifespan. The total carbon emissions were found to be 7066.21 tCO₂eq, with the production phase, including transportation, contributing the most at 47.01%, followed by the maintenance phase at 26.56%, the end-of-life phase at 24.67%, and the construction phase at only 1.72%. Permeable pavement showed considerable potential for energy savings and carbon reduction, achieving a net carbon reduction of 853.10 tCO₂eq. Sensitivity analysis identified diesel energy usage in maintenance, and the production and transportation of cement raw materials as the most impactful factors on the carbon footprint. Implementing specific carbon reduction measures, such as substituting coal gangue for

cement clinker, using manual instead of machine sweeping, and recycling all discarded materials, could significantly lower emissions. Thus, replacing traditional pavement with permeable pavement not only reduces the carbon footprint but also supports sustainable urban planning and development. Implementing specific carbon reduction measures, such as substituting coal gangue for cement clinker, using manual instead of machine sweeping, and recycling all discarded materials, could significantly lower emissions. Thus, replacing traditional pavement with permeable pavement not only reduces the carbon footprint but also supports sustainable urban planning and development.

However, this study has some limitations. Data were obtained from various literature and databases, necessitating updates and enhancements to ensure accuracy and reliability. The usage phase may have uncertainties because not all potential carbon emission reduction benefits were taken into account. Additionally, the economic impacts of different pavement types were not comprehensively considered, leaving a gap in evaluating the overall cost implications. Despite these constraints, this study highlights the benefits of carbon reduction and provides practical solutions for using permeable pavement in retrofitting aging communities, offering insights into sustainable development in the GBA. Future studies will delve into the cost–benefit analysis of permeable pavements versus traditional asphalt and cement pavements to provide a more comprehensive perspective to assess their economics and sustainability in different application scenarios. At the same time, the impact of raw material selection and design methods, such as the application of new low-carbon composites [84,85], will be explored to improve our understanding of the environmental benefits of permeable paving in a variety of application scenarios.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16177293/s1>. Table S1. Service life of permeable pavement in previous related studies. Table S2. Emission coefficients of carbon footprint inventories. Table S3. Transportation distance of manufactured materials. Table S4. Detailed information on the material transportation process in the end-of-life phase. Table S5. New mix proportion and corresponding material weight with gangue addition. Table S6. New mix proportion and corresponding material weight with fly ash addition. Table S7. Energy consumption for various maintenance method combinations in the maintenance phase. Figure S1. Uncertainty contribution analysis of the permeable pavement LCA inventory. Figure S2. Quality assessment of permeable pavement footprint inventory data. Figure S3. Sensitivity contribution analysis of list items.

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