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Carbon Emission Accounting and Multi-Objective Analysis for Steel Slag Road Paving: A Case Study from Xinjiang

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Abstract

The large-scale accumulation of steel slag from steelmaking and the over-exploitation of natural aggregates pose significant environmental and resource challenges. Focusing on the arid-cold region of Xinjiang, China, this study proposes the use of steel slag as a substitute for natural aggregates in pavement engineering. Through experimental performance evaluation and regionalized life cycle assessment (LCA), the technical feasibility and carbon reduction potential of this application were comprehensively evaluated. Results indicate that steel slag asphalt mixtures meet or exceed specification requirements in terms of high-temperature stability, water stability, and low-temperature crack resistance. However, volume stability decreases slightly with higher steel slag content and finer particle size, necessitating pretreatment for long-term durability. A local life cycle assessment model considering regional transportation factors was applied to the G30 Luhuo Expressway project. During the materialization stage, steel slag was used to replace 30% of the natural aggregates, reducing approximately 6718 kg of carbon dioxide equivalent emissions (31.4%). This, to some extent, reduced the extraction of natural resources, saved land resources, and alleviated the problems of resource shortage and price fluctuations. Sensitivity analysis reveals a positive correlation between carbon reduction and steel slag content, while transport distance strongly influences overall benefits, with a critical threshold of about 78 km defining the effective utilization range. Furthermore, a multi-objective optimization model balancing service life, cost, and carbon reduction was developed to identify an optimal steel slag content scheme, maximizing comprehensive benefits under constrained conditions. This work confirms the technical viability of steel slag pavement in extreme climates and provides a systematic framework integrating environmental benefits and logistical constraints, supporting regional industrial synergy and promoting circular economy practices in low-carbon infrastructure.

Keywords: steel slag pavement; carbon emission; carbon emission reduction; life cycle assessment (LCA); multi-objective optimization; Xinjiang

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1. Introduction

Since humanity stepped into the industrial society, the rapid development of mechanization and urbanization has consumed enormous amounts of fossil energy such as coal

and petroleum. This has led to a sharp increase in global greenhouse gas (GHG) emissions, resulting in severe damage to the ecological environment [1]. As one of the three major sources of CO_2 emissions [2], the transportation sector accounts for approximately 10% of the country's total carbon emissions [3]. Among this proportion, CO_2 emissions generated during the entire life cycle of road infrastructure construction and operation make up 10–20% of the total carbon emissions from road transportation. Moreover, China's road traffic infrastructure is currently in a period of strategic opportunity. By 2035, the scale of the national highway network and the ordinary national highway network will reach about 460,000 km, maintaining a stage of rapid development [4].

Nevertheless, large-scale highway construction is accompanied by significant carbon emission issues. According to estimates from the National Bureau of Statistics, China's highway construction consumes over 50 million tons of steel and 320 million tons of cement annually, with its whole-life-cycle carbon emissions accounting for approximately 28–35% of the total emissions in the transportation industry [5,6]. Meanwhile, the exploitation, processing, and long-distance transportation of natural aggregates such as sand and gravel consume substantial energy and generate emissions, exacerbating this problem. On the other hand, China's annual steel slag output exceeds 160 million tons, with a cumulative stockpile of around 1.8 billion tons, while its comprehensive resource utilization rate is only about 30%. Most of the steel slag is stored in open air, which not only occupies a large amount of land but also causes pollution to the soil, water resources, and air around the stockyards [7]. Therefore, the accumulation characteristics and cost advantages of steel slag, coupled with the limitations of traditional sand and gravel materials in road construction, form an ideal matching solution.

While prior research has investigated the utilization of industrial by-products (e.g., fly ash, slag) in civil engineering [8–10], most studies have centered on temperate or coastal regions, leaving a gap in understanding their performance under extreme climatic conditions such as those in Xinjiang—a region characterized by large diurnal and seasonal temperature variations, frequent freeze–thaw cycles, and arid environments. Furthermore, existing life cycle assessment (LCA) studies on steel slag pavements largely rely on generic emission factors and fail to incorporate region-specific variables (e.g., transportation distance), which exert a significant influence on net carbon reduction potential. Notably, there is a lack of a systematic framework that integrates material performance validation, spatially explicit carbon assessment, and multi-objective optimization, which constrains the capacity to support evidence-based decision-making in regional infrastructure planning. To address these research gaps, this study undertakes the following tasks: (1) systematically evaluate the pavement performance of steel slag asphalt mixtures under the unique climatic conditions of Xinjiang; (2) Develop a localized lifecycle model covering regional transportation factors from cradle to gate, and identify key thresholds for carbon reduction via sensitivity analysis; (3) propose a multi-objective optimization framework that balances service life, economic cost, and carbon reduction. These innovations provide novel theoretical and methodological support for the large-scale application of steel slag in pavement engineering within a resource-constrained and ecologically sensitive region.

2. Literature Review

2.1. The Applications of Steel Slag

Globally, steel slag is increasingly regarded as a valuable construction material. According to data from the World Steel Association, steel slag has been mainly used in road subgrades, construction, internal recycling, and agriculture in Japan, Germany, and the United States [11].

Based on statistics released by the Japan Steel Slag Association, Japan produced 12.005 million tons of steel slag in 2022, with a comprehensive utilization rate reaching 99.86%. Among this, 49.5% was applied to road construction, 6.2% to soil improvement, and 18.4% was recycled within the metallurgical process [12]. Most of Japan's steel slag is crushed and subjected to magnetic separation to recover iron contained in the slag. After the free calcium oxide (f-CaO) in the tailings is stabilized, almost all of it is used in road construction, cement and concrete manufacturing, and other fields.

According to data published by the German cement industry, Germany produced a total of 11.4 million tons of steel slag in 2023, with a comprehensive utilization rate of 95.61%. Concrete and cement production accounted for the largest proportion (57.89%) of steel slag utilization channels [13].

According to figures from the U.S. Geological Survey, the comprehensive utilization rate of steel slag in the United States was 86.7% in 2019, of which 44.4% was used for road construction, and only 13.3% was ultimately landfilled [14].

However, in recent years, developed countries have not stopped at this level of steel slag utilization. Portuguese scholar Caroline F.N. Moura and others argued that the transformation of the circular economy in road construction requires maximizing the use of alternative materials to reduce reliance on natural resources and minimize environmental impacts. They developed and verified an innovative hot recycled mix asphalt (HRMA) that incorporates steel slag aggregates (SSA) and reclaimed asphalt (RA). This mixture significantly reduces the demand for natural aggregates and virgin binders, strengthens the relevance of circular economy principles in pavement engineering, and promotes resource efficiency and sustainable road construction [15].

Spanish scholars Iván Salas et al. evaluated asphalt mixtures using electric arc furnace (EAF) steel slag as a sustainable aggregate for road construction. They adopted the batch leaching test (EN 12457-4) and the dynamic surface leaching test (DSLT, CEN/TS 16637-2) to analyze the leaching behavior of the asphalt mixtures. The study showed that EAF steel slag is a viable alternative for sustainable road construction, reducing natural resource consumption and advancing the circular economy [16].

From the above information, it can be concluded that the application of steel slag overseas, especially in road construction, has already entered a relatively mature stage. This is attributed to their early start, complete technical equipment, expansion into more application fields, and strict national supervision and management.

In recent years, domestic research on the application of steel slag as pavement material has also made considerable progress. Sun et al. aimed to achieve the efficient resource utilization of hydrochloride in pavement engineering. They treated silane with silane coupling agent (SCA) and explored its application in asphalt mixtures. Microscopic tests were conducted to study the interface modification mechanism of SCA-treated Chinese steel slag (SS). The results showed that SCA forms a polymer film on the surface of SS, effectively preventing water intrusion [17].

Wang Shuyong et al. systematically studied the static–dynamic intrinsic relationship between cement-stabilized steel slag and its destructive effect under explosive loads, aiming to improve the blast resistance of roads and realize the resource utilization of steel slag. The study indicated that compared with traditional cement-stabilized gravel, cement-stabilized steel slag has higher impact resistance, high-temperature durability, and long-term durability, making it an ideal alternative to gravel mixtures [18].

Liang He et al. studied the pavement performance of asphalt mixtures modified with crumb rubber/SBS composite binders and filled with waste steel slag powder in order to recycle waste steel slag and waste rubber in asphalt mixtures and improve road performance. They also discussed the environmental impact of the components in waste

steel slag powder. The results showed that compared with traditional asphalt mixtures (base asphalt and SBS-modified asphalt), the high-temperature rutting resistance was improved by 180% and 67.1%, the tensile properties were enhanced by 29% and 25.5%, and the water damage resistance was increased by 18.7% and 13.1%, respectively [19].

Heng Yuan et al. investigated the fatigue and self-healing properties of steel slag asphalt concrete as a pavement material in comparison with traditional diabase asphalt concrete. The results demonstrated that the addition of steel slag coarse aggregate significantly affects the fatigue life and stiffness modulus of asphalt concrete [20].

However, most existing studies have focused on temperate coastal or central regions, while regions like Xinjiang, which are characterized by an arid-semiarid climate, large day–night temperature differences, and frequent freeze–thaw cycles, impose stringent requirements on the durability and temperature stability of pavement materials. Meanwhile, as an important national energy and raw material base, Xinjiang has the dual characteristics of "concentrated steel production capacity" and "scarce natural aggregates". On the one hand, the problem of steel slag stockpiling in the region has become increasingly prominent, facing pressures of land occupation and environmental pollution. On the other hand, long-distance transportation of sand and gravel not only increases construction costs but also generates substantial carbon emissions during transportation.

Therefore, exploring the local resource utilization of steel slag in road engineering in Xinjiang is not only a solution to the regional problems of solid waste disposal and building material shortage but also a key exploration of a regional resource recycling model, which has a demonstration significance for maintaining the sustainable development of ecologically fragile areas. There is currently insufficient attention paid to the performance, long-term behavior, and carbon emission effects of steel slag pavement under an arid continental climate with large temperature differences and frequent freeze–thaw cycles (such as in Xinjiang).

2.2. Carbon Emission Assessment Methods for Road Construction

This project adopts the life cycle assessment (LCA) method, taking the entire life cycle of road paving using steel slag instead of traditional sand and gravel as the research object. Xiao et al. pointed out that the LCA method can connect links such as production, transportation, construction, usage, maintenance, demolition, and final disposal in a coherent system, so as to objectively assess environmental impacts [21].

LCA was first applied by Stripple to evaluate carbon dioxide emissions throughout the life cycle of road systems [22]. Since then, more scholars at home and abroad have conducted research on carbon emissions in the highway field using this method, such as the refined carbon footprint of traditional expressway construction [23], carbon emissions during the construction period of different pavement types [24], and road construction with new materials [25].

However, a key limitation of many existing LCA studies is that they adopt national or global average transportation and energy data, failing to reflect regional particularities. For regions like Xinjiang, which are rich in resources but face enormous logistics challenges, transportation distance becomes a crucial variable that may significantly alter the carbon balance of using alternative materials. Therefore, this study aims to address the above shortcomings by establishing a regionally adaptable LCA model and conducting multi-parameter sensitivity analysis so as to provide more refined insights for decision-making.

2.3. Multi-Objective Optimization

As a core component of transportation networks, highway construction is a complex project that exerts far-reaching impacts on ecology, society, and life-cycle costs. Traditional

single-objective decision-making centered on cost or traffic capacity often overlooks the environment, communities, and long-term sustainability. Against the backdrop of sustainable development requirements, how to seek optimal solutions amid multi-objective conflicts has become a core challenge, and multi-objective optimization provides a systematic modeling and solution method for this issue.

However, with the continuous improvement of highway construction standards, early single-objective management has had difficulty coping with project complexity, and research has gradually shifted towards multi-objective optimization. In the early stage, Liao Xiaohui et al. analyzed the optimization methods for highway construction network planning and established a quality–duration–cost optimization model that conforms to the characteristics of highway construction network planning [26]. Mungle, S et al. proposed a method based on the Fuzzy Clustering Genetic Algorithm (FCGA) to solve the problem of three conflicting objectives—time, cost, and quality—in construction projects [27].

In recent years, Jin Chang took the activity duration as the starting point, introduced system reliability and dependability, and established a multi-objective optimization model of duration–cost–quality [28]. Zhang Ying et al. constructed a duration–cost–quality multi-objective optimization model through the calculation of system reliability and dependability and obtained the optimal solution via the Improved Dynamic Multi-swarm Particle Swarm Optimization (IDM-PSO) algorithm [29]. Yao Yuquan et al. aimed to optimize the construction parameters of in situ hot recycling and reduce recycling construction costs. They analyzed the relationships between compaction degree and rolling temperature, regenerant dosage, as well as warm mix agent dosage, and established a prediction model for the compaction degree of in situ hot recycled asphalt pavement [30]. Researchers including Shahin F constructed a cost model for the in situ hot recycling construction of asphalt pavement and, accordingly, developed a multi-objective optimization model for construction parameters. The objective was to develop a multi-objective optimization model to address these challenges by simultaneously considering the safety, mobility, and project costs of highway construction zones. The genetic algorithm was adopted to identify the Pareto frontier, clarifying the trade-offs among safety, mobility, and cost. It evaluated various decision variables related to site geometry, work zones, and other factors [31].

Therefore, on the basis of inheriting the research thread of multi-objective optimization, focusing on the collaborative analysis and optimization of steel slag pavement in various dimensions is not only a key entry point to meet the current demands of green transformation and sustainable development in highway construction but also provides a scientific decision-making framework for the high-value utilization of industrial solid waste.

3. Material and Experiments

3.1. Raw Materials

The SBS I-C-modified asphalt and 70# asphalt used in the experiment were supplied by PetroChina Karamay Petrochemical Company. Meanwhile, four grades of steel slag with particle sizes of (a) 0–3 mm, (b) 3–5 mm, (c) 5–10 mm, and (d) 10–15 mm were adopted (see Figure 1).

3.1.1. Mix Proportion Design of Mixture

To investigate the effect of steel slag particle size on the mixture, Mix #1, which uses 100% natural aggregates (red sandstone and limestone), was the control group. Then, steel slag with different particle size ranges was used to replace the stone aggregate, respectively, to prepare five types of asphalt mixtures. The material composition is shown in Table 1. Among them, mineral powder was used to improve the compactness and workability of the asphalt mixture during construction.



Figure 1. Steel slag of different particle sizes.

Table 1. Material Composition of Different Asphalt Mixtures.

Material Combination Number	Steel Slag Substitution Position	Type of Aggregate				Mine Powder	Asphalt
		10~15 mm	5~10 mm	3~5 mm	0~3 mm		
1#	Control Group	Red sandstone	Red sandstone	Red sandstone	Limestone	Limestone	SBS
2#	Alternative: 10–15 mm	Steel slag	Red sandstone	Red sandstone	Limestone	Limestone	SBS
3#	Alternative: 5~10 mm	Red sandstone	Steel slag	Red sandstone	Limestone	Limestone	SBS
4#	Alternative: 3~5 mm	Red sandstone	Red sandstone	Steel slag	Limestone	Limestone	SBS
5#	Alternative: 0~3 mm	Red sandstone	Red sandstone	Red sandstone	Steel slag	Limestone	SBS

Gradation optimization was conducted based on volumetric parameters such as void ratio and voids in mineral aggregate (VMA), and the mass ratios of each mixture were determined (see Table 2).

Table 2. Quality Ratios of Different Asphalt Mixtures.

Material Type	Bulk Density of the Material (g/cm)	1#	2#	3#	4#	5#
Red sandstone 10~15 mm	2.608	28	0	0	0	0
Steel slag 10~15 mm	3.258	0	30.7	30.9	28.7	34.6
Red sandstone 5~10 mm	2.613	24	22.5	0	0	0
Steel slag 5~10 mm	3.268	0	0	26.6	26.1	25.1
Red sandstone 3~5 mm	2.618	14	13.1	12.4	0	0
Steel slag 3~5 mm	3.307	0	0	0	14.1	13.6
Limestone-based aggregate	2.602	29	27.0	25.6	25.1	0
Steel slag 0~3 mm	2.987	0	0	0	0	27.8
Mine powder	2.655	5	4.8	4.5	4.4	4.3

According to the method stipulated in "Test Procedures for Asphalt and Asphalt Mixtures in Highway Engineering" (JTG E20—2011) T 0702, standard Marshall specimens were prepared. The maximum theoretical relative density of the mixture was calculated based on the effective relative density of the aggregates determined by the asphalt immersion method. The volume indices, Marshall stability, and flow values of the mixtures under different asphalt-to-aggregate ratios were te sted, and then the optimal asphalt-to-aggregate ratio for different asphalt mixtures was determined. The optimal asphalt-to-aggregate ratios for different steel slag asphalt mixtures are shown in Table 3.

Table 3. The optimal asphalt-to-aggregate ratio for different mixtures.

Type of Mixture	1#	2#	3#	4#	5#
Quality stone-to-oil ratio (%)	5.0	4.9	4.9	5.0	5.0
Volume-to-grit ratio (%)	12.69	13.44	14.21	14.75	15.20

3.1.2. Road Performance of Steel Slag Concrete

This subsection will conduct adaptability tests on the pavement performance of steel slag concrete and evaluate the performance impacts through the analysis of basic properties of raw materials, high-temperature stability, water stability, low-temperature cracking resistance, and volume stability. In the research, the steel slag refers to the steel slag in asphalt concrete, rather than the coarse or fine aggregates in rigid concrete. The experiment shows that all the pavement performance indicators of steel slag asphalt mixtures meet the requirements specified in the relevant specifications. Compared with ordinary asphalt mixtures, their high-temperature stability (Figure 2), water stability (Figures 3 and 4), and low-temperature crack resistance (Figures 5 and 6) are all improved; however, their volume stability is slightly reduced (Figures 7–9), and this trend becomes more pronounced with the increase in steel slag content and the decrease in particle size. The types, sizes, and replication times of the experimental samples are shown in Table 4.

TSR stands for tensile strength ratio, which is the ratio of the indirect tensile strength of freeze–thaw conditioned specimens to that of unconditioned specimens, expressed as a percentage. It is a key indicator for evaluating the moisture susceptibility and freeze–thaw resistance of asphalt mixtures.

Table 4. The types, sizes, and replication times of the experimental.

Test	Specimen Type	Dimensions	Replicates
Rutting test (High-temperature stability)	Plate specimen	300 mm × 300 mm × 50 mm	3 per mixture
Immersion Marshall Test (Water stability)	Cylindrical specimen	Φ101.6 mm × 63.5 mm	4 per condition
Freeze–thaw splitting test (Water stability)	Cylindrical specimen	Φ101.6 mm × 63.5 mm	4 per condition
Low-temperature bending test (Crack resistance)	Beam specimen	250 mm × 30 mm × 35 mm	4 per mixture
Volume expansion test	Cylindrical specimen	Φ101.6 mm × 63.5 mm	3 per mixture

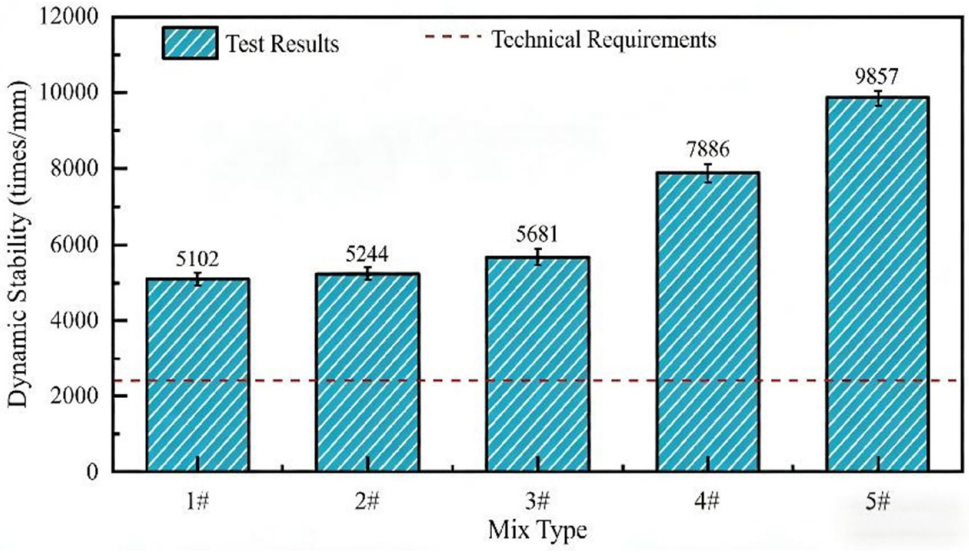


Figure 2. Rutting Test Results.

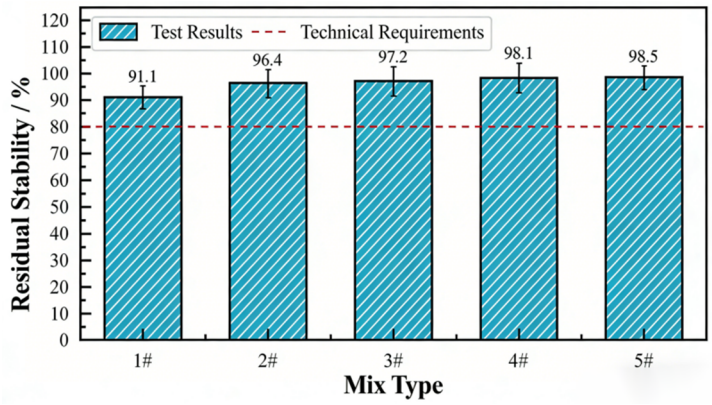


Figure 3. Results of Water Immersion Marshall Test.

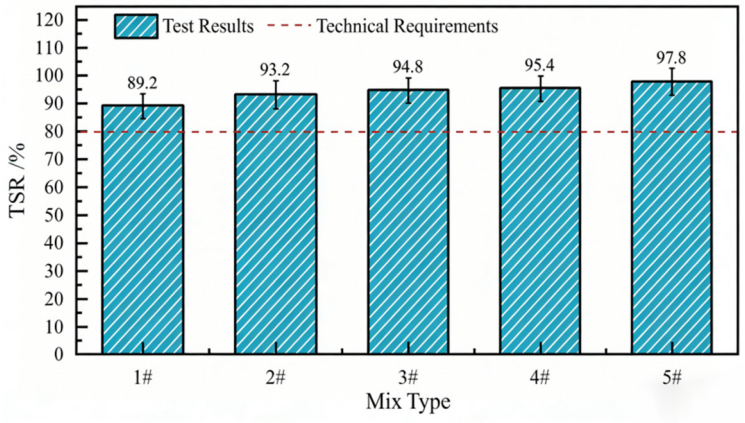


Figure 4. Results of Freeze–Thaw Splitting Test.



Figure 5. Low-temperature bending test.

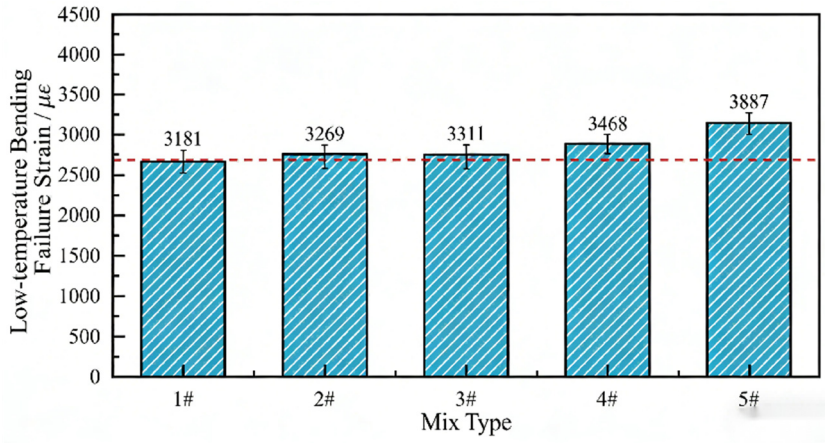


Figure 6. Results of Low-Temperature Bending Test.

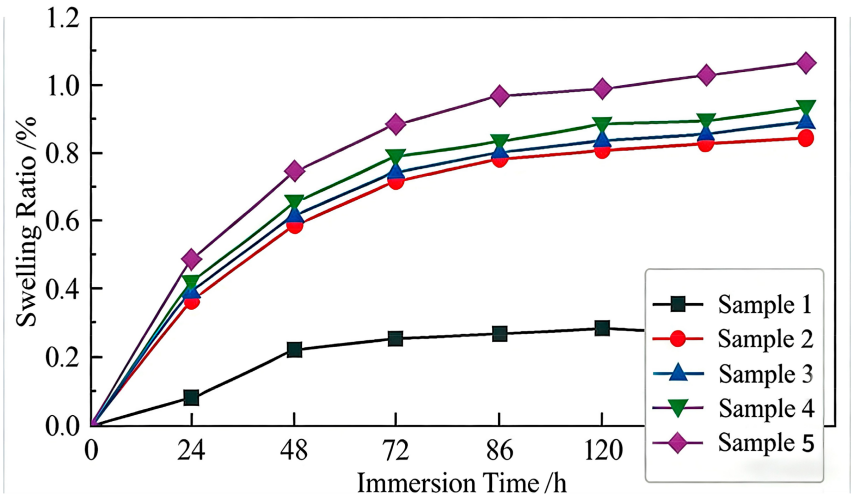


Figure 7. Relationship between mixture expansion rate and time.

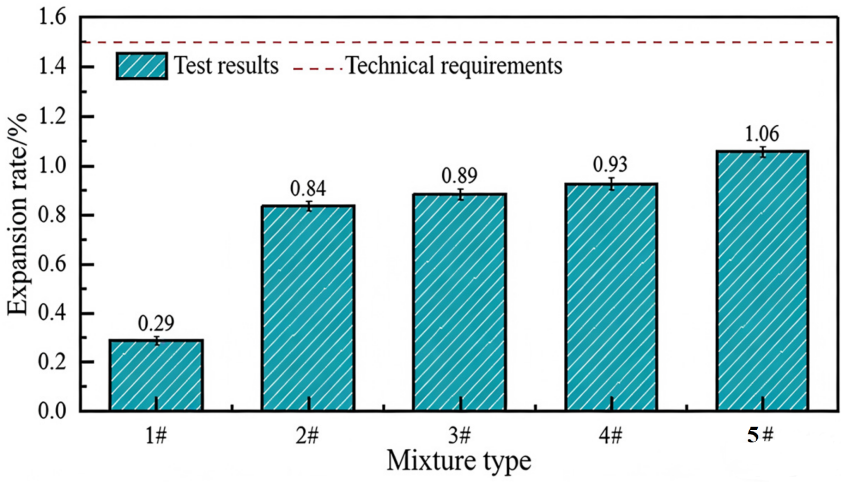


Figure 8. Results of the asphalt mixture expansion test.



Figure 9. White crystalline substances have precipitated on the surface of the 5# mixture specimen.

3.2. Establishment of Carbon Emission Model for Steel Slag Pavement Construction

3.2.1. System Boundary

This study focuses on the physicochemical stage of road pavement within the system boundary. According to the time sequence of construction activities, the carbon dioxide emissions associated with steel slag pavement are divided into three phases. However,

within the framework of this study, since steel slag is a waste product generated after steel production in steel mills, it is defaulted that the carbon emissions of steel slag during the production stage of building materials are not included in the carbon emission accounting for highway pavement construction processes. Therefore, in this case, the carbon emission accounting for steel slag only covers the carbon emissions during the transportation stage and the construction stage (Figure 10).

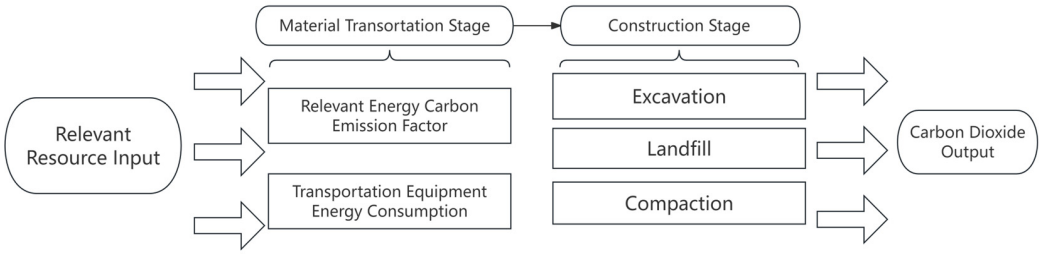


Figure 10. System boundary.

Carbon emissions during the material transportation stage refer to those generated in the process of transporting steel slag from steel mills to construction sites. The hourly fuel consumption of transport vehicles is referenced to the public data and specifications from the Zhongke Digital Low-Carbon and Dual-Carbon Data Service Platform. For the selected diesel heavy-duty trucks with a load capacity of less than 30 tons, the unit transportation carbon emission intensity is 0.078 kg $CO_2e/(t{\cdot}km)$.

The carbon emissions generated during pavement construction include the total carbon dioxide emissions produced in the excavation, landfill, and compaction stages. The performance data and carbon emission factors of the construction equipment involved in the calculation are shown in Table 5 (the fuel consumption rates of the equipment and the data in the table are all referenced from the manufacturers' specifications and the field measured data of similar projects).

Table 5. Equipment during Construction Phase.

Constrution Phase	Construction Equipment	Efficiency	Consumption	Carbon Emission Factor
Excavation	Medium-sized excavator	150 m^3/h	15 L/h	3.1 kg CO_2eq
Landfilling	Medium-sized tire loader	75 m^3/h	13 L/h	3.1 kg CO_2eq
Compaction	Steam Vibratory Compactor	400 m^3/h	1 L/h	3.1 kg CO_2eq

3.2.2. Carbon Emission Accounting Model

This section will take the partial reconstruction and construction section of the Lianhuo Expressway (G30) as the research object to establish the model. The project is divided into three survey and design tenders (HTGTSJ-1, HTGJSJ-2, HTGJSJ-3) and one survey and design geological prospecting supervision and design consulting section (HTSJZX-1). The research focuses on the HTGJSJ-3 section, with a total length of 25.06 km and a width of 30 m. The steel slag used in the HTGJSJ-3 section is mainly applied to the pavement structure of the central line expansion. In the pavement structure, steel slag is mainly used in the middle surface course and the base course of the pavement structure for the main road expansion, with its content not less than 30%. When steel slag asphalt concrete is used, the proportion of steel slag in the total aggregate should not be less than 30%. According to the construction design of this project, the amount of sand and gravel replaced in each pavement structure is shown in Table 6.

Table 6. Quantities of Sand and Gravel Substituted for Each Layer.

Location	Content of Replaced Sand and Gravel Materials (m^3)
Basement level	2231.2152
Middle layer	798.51
Leveling layer	52.023
Total	3081.7482

(1) Carbon Emission Total Quantity Accounting Model

The emissions associated with pavement construction are the sum of the emissions from the two aforementioned stages. The carbon emission factor method was adopted to establish a carbon emission accounting model for the whole life cycle of construction. The carbon emissions of highway construction were calculated by stages, and finally, the total carbon emissions of the whole life cycle of construction were summarized. The final unit of carbon emissions in the model is kilogram carbon dioxide equivalent, namely, kg CO_2e. The calculation of each stage in the carbon emission life cycle is shown in the following formula.

$$E = E_t + E_C \quad (1)$$

In the formula,

E—Total carbon emissions during the building's life cycle (kg CO_2e);

Et—Total carbon emissions during the transportation stage (kg CO_2e);

E_C—Total carbon emissions during the construction phase (kg CO_2e).

(2) Carbon emission accounting model for the transportation stage

Carbon emissions in the transportation stage mainly arise from fuel consumption of vehicles transporting construction materials, which stem from the fuel consumption of transport vehicles. In practical research, calculations are generally carried out by category according to the construction machinery information specified in the construction project budget. The transportation distance of construction materials needs to be determined based on different material types. To facilitate calculation and eliminate relevant interfering factors, this study assumes that the transportation distance of each material is 50 km. Therefore, the carbon dioxide emissions are determined by multiplying the number of vehicle trips, the fuel or energy consumed per shift, and the emission factor corresponding to the fuel or energy. The calculation formula for carbon emissions in this stage is as follows:

$$\mathrm{E_t} = D \times \mathrm{M} \times \mathrm{EF} \quad (2)$$

In the formula,

E_t—The carbon emissions generated during the process of transporting materials by trucks, kg;

D—Average one-way transportation distance (km);

M—Total weight of materials (tons);

EF—Transportation carbon emission factor (kg CO_2e/(t·km)).

Note that material weight M is expressed in metric tons (t) in Equation (2) to align with the unit of the transportation emission factor EF (kg CO_2e/(t·km)). The material volumes provided in Table 6 (in m^3) are converted to tons using the bulk densities of the respective materials, as listed in Table 2, to ensure consistent and accurate emission calculations.

(3) Carbon emission accounting model during the construction phase

The accounting method refers to the basic formulas specified in Code for Carbon Emission Accounting of Highway Infrastructure Construction (DB15/T 2882-2023) and Standard for Calculation of Carbon Emissions During Highway Construction Period (T/CHSDA 0001-2024). Fully considering the climatic particularities of the Xinjiang region, a correction

coefficient for mechanical energy consumption in alpine or sandy regions is added. In addition, due to the differences in fuel consumption among various construction machinery on the construction site, when calculating carbon emissions during the construction phase, it is necessary to convert the actual usage of various machinery in the construction process into specific fuel consumption and then multiply it by the corresponding fuel carbon emission coefficient. The total carbon emissions during the construction phase are the sum of the fuel carbon emissions of all construction machinery, and the specific calculation formula is as follows:

$$E_C = \sum (N_j \times F_j \times FC_j) \quad (3)$$

In the formula,

E_c—Carbon emissions generated by mechanical equipment operations, kg;

j—Type of mechanical equipment j, j = 1. . .. . .n;

N_j—The quantity of mechanical equipment j, Shift of equipment;

F_j—Mechanical equipment j Fuel and material consumption per shift, kg. Refer to the values specified in Appendix C of the Group Standard for Carbon Emission Accounting of Highway Maintenance Projects;

FC_j—The CO_2 emission factor of the fuel materials used in mechanical equipment J, kg CO_2/kg or kg CO_2/kWh. Refer to the values in Appendix C of the Group Standard for Carbon Emission Accounting of Highway Maintenance Projects.

4. Results and Discussion

4.1. Carbon Emission Reduction

The established LCA model was applied to the case of the G30 Expressway to quantify the carbon emissions at each stage (as shown in Table 7). The total carbon emissions of the steel slag scheme (with a replacement rate of 30%) reached 14,653.7 kg CO_2e, while that of the traditional aggregate scheme stood at 21,371.9 kg CO_2e (as shown in Table 8). This is equivalent to achieving a net carbon emission reduction of 6718.2 kg CO_2e (approximately 31.4%), which is mainly attributed to the avoidance of carbon emissions during the emission-intensive production stage of natural aggregates. On the basis of obtaining the carbon emission data of pavement construction with 30% steel slag content, the carbon emissions of sand and gravel materials at each stage without steel slag replacement were derived in accordance with the theory of life cycle assessment (LCA) and the research findings presented in [32–34].

Table 7. Carbon Emission Data for Different Stages with 30% Steel Slag Content.

	Carbon Emissions (kg CO_2eq)			Total Carbon Emissions (kg CO_2eq)
Transportation stage	12,018.8			14,653.721
Construction phase	Excavation	Landfilling	Compaction	
	955.11	1655.927	23.884	

Table 8. Carbon Emission Data for Each Stage of Unutilized Steel Slag.

	Production Stage	Transportation Stage	Construction Phase
Carbon emissions (kg CO_2eq)	6718.21	12,018.8	2634.921
In total (kg CO_2eq)		21,371.931	

4.2. Sensitivity Analysis

(1) Sensitivity Analysis of Steel Slag Content and Carbon Emission Reduction

This case analysis quantifies carbon emissions based on a fixed steel slag content, but it does not fully reflect the difference in the impact of varying steel slag contents on carbon emissions. Therefore, the study will conduct a sensitivity analysis by assuming that the steel slag content is increased or decreased at a ratio of 5% and then calculate the carbon emission reduction. The corresponding relationships between different steel slag contents and carbon emission reductions are shown in Figure 11.

The scope of this project, each 5% increase in the replacement rate can reduce emissions by approximately 1120 kg CO_2e. The formation of this emission reduction trend is mainly due to the fact that as the amount of steel slag used increases, the consumption of sand and gravel in the production stage decreases accordingly, which, in turn, leads to a reduction in carbon emissions from processing equipment and fewer transportation shifts during the transportation process. This highlights the dual benefits of steel slag utilization in waste absorption and reducing the demand for primary materials.

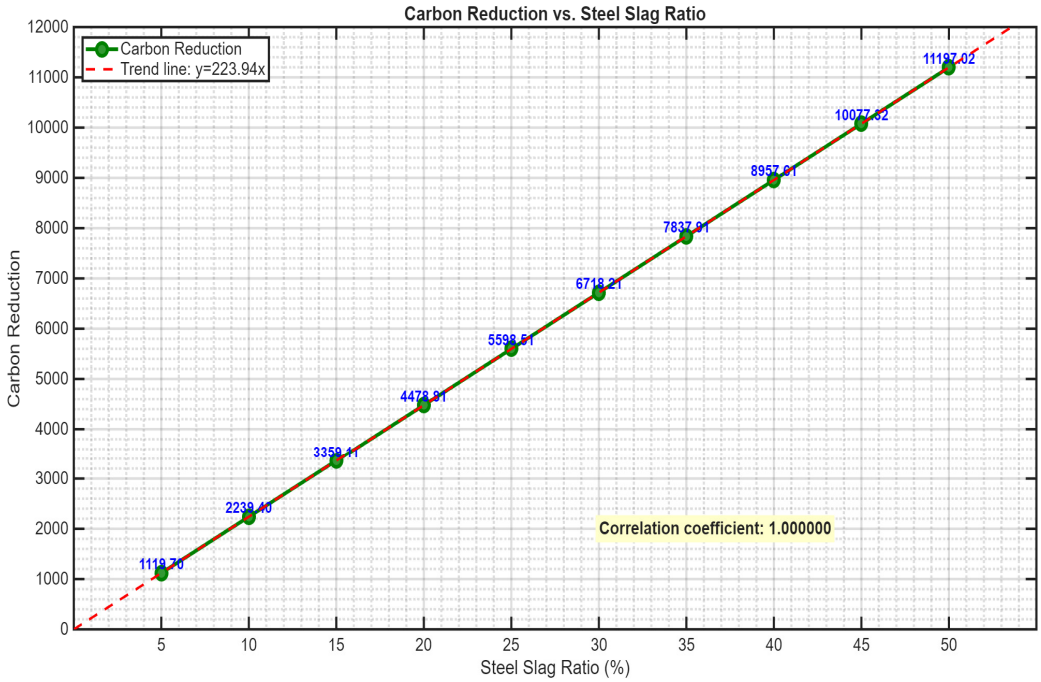


Figure 11. Carbon emission reduction under different steel slag contents.

(2) Sensitivity Analysis of Transportation Distance and Carbon Emissions

In the specific carbon emission accounting mentioned above, the carbon emissions from the transportation stage account for the largest proportion of the total carbon emissions. This is because transportation distance, as a key variable, directly determines the fuel consumption and emissions in the transportation stage. However, although steel slag has emission reduction advantages in the production stage, these benefits may be offset if the transportation distance is excessively long. This section will adjust the transportation distance to investigate the impact of changes in transportation distance on total carbon emissions, identify the critical transportation distance, and ensure the carbon emission reduction effect of steel slag pavement construction. The relevant parameters and assumptions are presented in Table 9.

Table 9. Parameters and Assumptions for Sensitivity Analysis of Transportation Distance.

Parameters	Numerical Value	Explanation
Demand for steel slag	3081.7482 t	Total demand for road construction materials
Unit transportation carbon emission intensity	0.078 kg CO_2e/(t·km)	30-ton diesel heavy truck transportation
Carbon emissions in other stages	2634.921 kg CO_2e	The total sum of pre-treatment, laying, compaction, etc.
Carbon emissions of the traditional sand and gravel material solution	21,371.931 kg CO_2e	As a benchmark
Base transportation distance	50 km	Analysis reference benchmark point

Based on the set parameters and assumptions, carbon emissions are calculated under different transportation distances, as shown in Table 10:

Table 10. Carbon Emission Calculation under Different Transportation Distances.

Transportation Distance (km)	Transportation Carbon Emissions (kg CO_2e)	Total Carbon Emissions (kg CO_2e)	Transportation Share	Change Rate Relative to the Benchmark
10	2403.8	5038.7	47.7%	−58.1%
20	4807.5	7442.4	64.6%	−38.1%
50 (Benchmark)	12,018.8	14,653.7	82.0%	0%
80	19,230.1	21,865.0	88.0%	+49.2%
100	24,037.6	26,672.5	90.1%	+82.0%
120	28,845.1	31,480.0	91.6%	+114.9%
150	36,056.4	38,691.3	93.2%	+164.1%

From the calculation results, it can be seen that carbon emissions have a strict linear relationship with transportation distance. For every 1 km increase in transportation distance, the total carbon emissions increase by approximately 240.376 kg CO_2e. Therefore, the critical transportation distance D is as follows.

When the carbon emissions of the steel slag solution are equal to those of the traditional sand and gravel solution:

$$E = E_t + E_C \quad (4)$$

$$\mathrm{E_t} = D \times \mathrm{M} \times \mathrm{EF} \quad (5)$$

In the formula,

E—Total carbon emissions during the building's life cycle (kg CO_2e);

Et—Total carbon emissions during the transportation stage (kg CO_2e);

E_C—Total carbon emissions during the construction phase (kg CO_2e);

E_t—The carbon emissions generated during the process of transporting materials by trucks, kg;

D—Average one-way transportation distance (km);

M—Total weight of materials (tons);

EF—Transportation carbon emission factor (kg CO_2e/(t·km)).

Therefore, based on the above formula, the following relationship is derived:

D × 240.376 + 2634.921 = 21,371.931

D ≈ 77.95 km

Therefore, by analyzing the sensitivity of transportation distance and carbon emissions, the following conclusion was reached:

(1) High sensitivity to transportation distance: The transportation distance has a significant impact on the carbon emissions of the steel slag scheme, showing a linear positive correlation.

(2) There is a critical point: The critical transportation distance is approximately 77.95 km. Beyond this distance, the steel slag solution loses its advantage in carbon reduction.

4.3. Scenario Analysis of Carbon Emission Reduction Potential Based on Multi-Objective Optimization

4.3.1. Basic Definitions and Model Framework

(1) Definition and Calculation Framework for Carbon Emission Reduction Potential of Steel Slag Pavement

The carbon emission reduction potential of steel slag pavement maintenance projects refers to the potential of reducing greenhouse gas emissions throughout the whole life cycle by replacing traditional natural sand and gravel with a specific content of steel slag in pavement maintenance projects. This potential is characterized in the form of a percentage, and its core stems from the avoidance of carbon emissions during the production stage of natural aggregates. In this study, referring to the G30 project case, a three-dimensional evaluation framework of "service performance—economic cost—carbon emission reduction benefit" is still constructed. Combined with the engineering characteristics of steel slag materials, the content of steel slag is incorporated into the potential calculation system as a key decision-making variable.

(2) Carbon Emission Reduction Potential Calculation Method

The calculation of carbon reduction potential (CRP) is based on the comparative analysis principle of life cycle assessment (LCA). By setting a baseline scenario (using traditional natural aggregates) and multiple low-carbon scenarios (using mixtures with different steel slag contents), the difference in carbon emissions between the two throughout the whole life cycle is calculated. The basic formula is as follows:

$$CRP_j = \frac{C_{RV} - C_{LC,j}}{C_{RV}} \times 100\% \quad (6)$$

In the formula, CRP_j represents the carbon emission reduction potential (in percentage) when using the jth steel slag addition scheme; C_{RV} represents the total life cycle carbon emission (in kg CO_2e) of the baseline scenario; $C_{LC,j}$, represents the total life cycle carbon emission (in kg CO_2e) of the low-carbon scenario when using the jth steel slag addition scheme.

4.3.2. Data Preparation

(1) Section division

According to Section 3.2.2 of the supporting project, the length of the HTGJSJ-3 section is divided into five equal subsections as shown in Table 11.

Table 11. Section Division and Milepost Numbers.

Section Number	Pile Number
1	K3337+000~K3342+000
2	K3342+000~K3347+000
3	K3347+000~K3352+000
4	K3352+000~K3357+000
5	K3357+000~K3362+000

(2) Service life of the road surface

The service life of the pavement is characterized by the first maintenance time T(x), an indicator that is directly correlated with the deterioration process of the pavement condition index (PCI). Based on the exponential standard deterioration equation proposed by Professor Sun Lijun [35] and with reference to the follow-up study on a steel slag asphalt pavement test section of an expressway conducted by Zhang Mengjin et al. [36], the PCI

deterioration models for the ordinary pavement and the pavement with 50% steel slag content are presented as follows:

Ordinary asphalt mixture pavement:

$$PCI = 94[1 - e\left(-\frac{11}{y}\right)^{0.8}] \quad (7)$$

Steel slag asphalt mixture pavement:

$$PCI = 96[1 - e\left(-\frac{14}{y}\right)^{0.8}] \quad (8)$$

The maintenance threshold of PCI = 70 was selected based on the Chinese technical specification for highway pavement maintenance design (JTG 5421-2018), which identifies PCI = 70 as the critical value separating "good" pavement condition (requiring preventive maintenance) from "fair" condition (requiring more intensive rehabilitation). This threshold is consistent with both domestic standards and international practice, ensuring that the calculated first maintenance times reflect realistic intervention triggers in pavement management. Therefore, we set the maintenance threshold to PCI = 70 and calculate the corresponding first maintenance time:

$$T(0) \approx 6.55 \text{ year}, \ T(0.5) \approx 10.03 \text{ year}$$

Assuming that the service life is linearly related to the steel slag content within the commonly used range in engineering, a function for the relationship between the steel slag content and the expected service life can be established:

$$F1 = 6.55 + 6.96x$$

(2) Cost

The cost analysis covers the maintenance and repair expenses during the construction period and the 15-year operation period.

Based on the research by Wang Hongxiang et al. [37] on the economic benefits of steel slag asphalt pavement in Hunan Province, the construction cost $C_c(x)$ and the annual value of maintenance costs $C_m(x)$ can be expressed as

$$C_c(x) = 48.8 - 8.16x \quad (9)$$

$$C_m(x) = 12.4 - 4.392x \quad (10)$$

Considering the transportation distance of steel slag d = 77.95 km, the discount rate is set at 10% (refer to the "Economic Evaluation Methods and Parameters for Construction Projects" issued by the National Development and Reform Commission [38]), the analysis period is 30 years, and the discount factor is

$$\sum_{t=1}^{30} \frac{1}{(1+0.1)^t} \approx 9.4269 \quad (11)$$

Therefore, establish the relationship function between steel slag and cost:

$$F_2 = C_c(x) + 9.4269 \times C_m(x) = 165.6936 - 54.647x \quad (12)$$

(3) Carbon emission reduction

Based on the carbon emission results calculated in Section 4.1, it is determined that with a 30% steel slag addition rate, carbon emissions can be reduced by 6718.21 kg CO_2e, representing an emission reduction ratio of approximately 31.4%.

Assuming that the carbon emission reduction intensity per unit remains constant, a linear emission reduction model is established:

$$\Delta E(X) = \frac{6718.21}{0.3} \approx 22394.03x \tag{13}$$

Therefore, the carbon emission reduction model is

$$F3 = 22394.03x \tag{14}$$

(4) Decision on the proportion of steel slag

Volume stability is the primary factor limiting the content of steel slag. Technical Specifications for Construction of Highway Asphalt Pavements (JTG F40) stipulates that the free calcium oxide content in steel slag shall not exceed 3%, and the water immersion expansion rate shall not exceed 2%; however, in practical engineering, considering uncontrollable factors, the allowable water immersion expansion rate is set at no more than 1.5%. According to the design requirements of the reconstruction and expansion project of G30 Lianhuo Expressway, the proportion of steel slag in the total aggregate should not be less than 30%, which serves as the minimum technical requirement for the resource utilization of steel slag in practical engineering. Research conducted by Mo Liantong et al. [39] indicates that the water immersion expansion rate of steel slag is strongly positively correlated with its f-CaO content. When the f-CaO content of raw steel slag is 2.3% (with a steel slag content of approximately 50%), its water immersion expansion rate reaches 1.5%, approaching the specified limit of 2% with a limited safety margin. In addition, in the mix proportion design of practical engineering, the content of steel slag in aggregates is usually not more than 50% to ensure long-term volume stability. Therefore, considering raw material control and engineering practice, the upper limit of the technically feasible range is set at 50%.

Finally, based on the established cost function, budget documents, project reports and construction drawings, a summary and collation were carried out to obtain the unit carbon emission reduction, average cost, and service life under various content levels, with the statistical data presented in Table 12.

Table 12. Model Data Statistics.

Steel Slag Content (%)	Unit Carbon Emission Reduction (kg CO_2e/m^2)	Cost (yuan/m^2)	Service Life (year)
30	0.225	49.77	8.6
35	0.262	48.87	9.0
40	0.300	47.93	9.3
45	0.337	47.03	9.7
50	0.375	46.13	10.0

4.3.3. Multi-Objective Model Construction

(1) Establishment of multi-objective optimization model

This research decision-making model aims to achieve the coordinated optimization of the following three goals:

1. G1: Maximize the overall service life within the planning period.
2. G2: Minimize the total maintenance cost within the planning period.
3. G3: Maximize the total carbon emission reduction within the planning period.

The multi-objective optimization model is established as follows:

$$maxG1 = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} SL_{ij} \quad (15)$$

$$minG2 = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} C_{ij} A_i \quad (16)$$

$$maxG3 = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} E_{ij} A_i \quad (17)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} C_{ij} A_i \leq B \quad (18)$$

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall i \quad (19)$$

$$SL_{ij} > SL_{min} = 6 \quad (20)$$

In the formula,

i—Section Number, i = 1, 2, . . ., m;

j—Steel slag content grade designation, j = 1, 2, . . ., n, Corresponding dosage 30%, 35%, . . . 50%;

x_{ij}—Decision variable, indicating whether section i adopts the jth steel slag dosage scheme, with values of 0 or 1;

L_i—The length of section i (kilometers);

W_i—The width of section i (meters);

A_i—$L_i \times W_i$: The paved area of section i (square meters);

SL_{ij}—The predicted service life (years) of section i when using the jth type of dosage;

Cij—The unit area laying cost (yuan per square meter) when using the jth dosage for section i;

Ei—The unit area carbon emission reduction amount (kg CO_2e per square meter) when section i adopts the jth type of dosage;

B—Total construction budget (ten thousand yuan);

SL_{min}—Minimum allowable service life of pavement (years);

x—Percentage of steel slag content;

B—Budget throughout the entire life cycle (ten thousand yuan).

4.3.4. Analysis of Carbon Emission Reduction Potential

Based on the multi-objective optimization model constructed in Section 4.3.2, a quantitative analysis was conducted. By defining the planning period, budget, and performance constraints, a multi-objective optimization algorithm was adopted for model solution, and a steel slag content allocation scheme that balances service life, economic cost, and carbon emission reduction benefits was obtained. On this basis, the overall carbon emission reduction potential of the road section under the background of steel slag resource utilization was evaluated.

The improved Non-dominated Sorting Genetic Algorithm II (NSGA-II) was used to solve the model. The planning period was set at 15 years, the upper limit of the total budget was B = 1.2 × 104 ten thousand yuan, and the minimum required service life was SLmin = 6 years.

To solve this multi-objective optimization problem, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was employed to search for the Pareto optimal solution set. The algorithm parameters were set as follows: the population size was 100, the maximum number of iterations was 300, the crossover probability was 0.8, and the mutation probability was 0.1. The optimization objectives included maximizing the total service life (G1), minimizing the total cost (G2), and maximizing the total carbon emission reduction (G3). After obtaining the Pareto frontier, the Technique for Order Preference by Similarity to an

Ideal Solution (TOPSIS) was used to screen out the compromised scheme with the optimal comprehensive evaluation from the solution set.

After 300 iterations of calculation, a Pareto optimal frontier containing approximately 120 non-dominated solutions was obtained. Using the TOPSIS method and with equal weights assigned to each objective as the decision preference, a recommended scheme was selected from the Pareto solution set, and the Pareto optimal solution set is shown in Figure 12. The key target values corresponding to this scheme are as follows: the total service life is 9.94 years per kilometer, the total cost is 44.25 million yuan, and the total carbon emission reduction within the 15-year planning period is 275,550 kg CO_2e. Compared with the baseline scenario where traditional natural aggregates are fully adopted, the carbon emission reduction potential (CRP) achieved by this optimized scheme is calculated as follows:

$$CRP_j = \frac{C_{RV} - C_{LC}}{C_{RV}} \times 100\% \approx 51.3\% \quad (21)$$

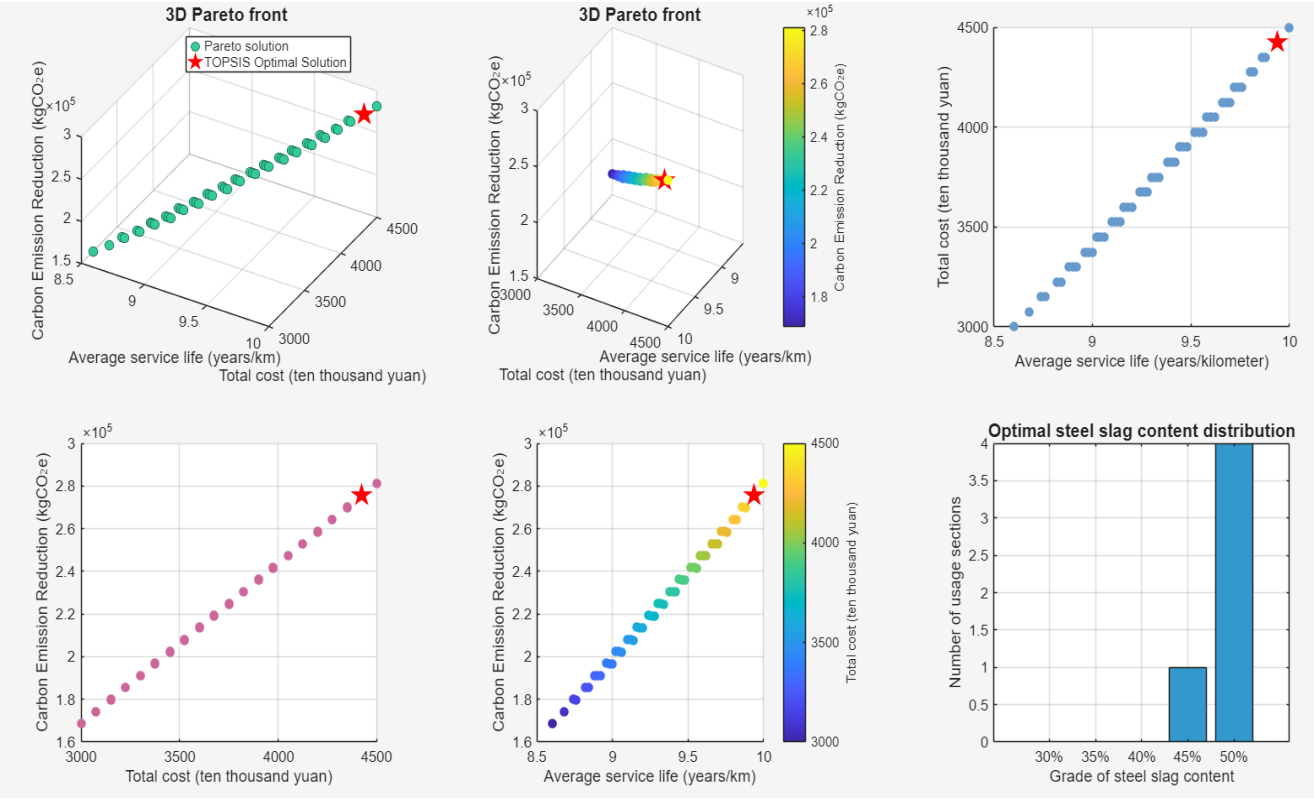


Figure 12. Results of Multi-objective Optimization.

In summary, by constructing and solving a multi-objective optimization model, this section clarifies the optimal content allocation strategy for steel slag asphalt mixture in the maintenance of Section HTGJSJ 3 of G30 Expressway and quantifies its carbon emission reduction potential at approximately 51.3%. This result not only verifies the feasibility of achieving the synergistic optimization of performance, cost, and environment for steel slag in pavement engineering but also provides a quantitative decision-making basis for promoting the resource utilization of industrial solid wastes and formulating low-carbon maintenance strategies in similar regional engineering projects.

5. Conclusions

Through systematic laboratory tests and a localized life cycle assessment (LCA) model, this study comprehensively evaluated the technical feasibility, environmental benefits, and

multi-objective optimization potential of using steel slag in asphalt pavement engineering in the arid-cold region of Xinjiang. The main conclusions are as follows:

(1) Technical Feasibility

Steel slag asphalt mixtures exhibit excellent pavement performance. Their high-temperature stability, water stability, and low-temperature crack resistance surpass those of traditional mixtures, meeting the requirements of relevant Chinese technical specifications. It should be noted that volume stability decreases somewhat with increasing fine steel slag content, necessitating pretreatment processes such as natural aging, water spraying, or thermal treatment to stabilize expansive components (primarily f-CaO and f-MgO) and ensure long term durability.

(2) Carbon Emission Reduction Potential

The regionalized LCA model proposed in this study quantifies the significant carbon emission reduction effect brought by replacing natural aggregates with steel slag. In the case of the G30 Expressway, a 30% replacement rate reduced the carbon emissions of the studied pavement layer by 31.4% during the "cradle-to-gate" stage. Meanwhile, the sensitivity analysis shows that the carbon emission reduction benefit is highly sensitive to transportation distance. The study identified a critical threshold of approximately 83 km, which sets the maximum recommended transportation distance to ensure net carbon benefits under current typical transportation conditions.

(3) Multi-objective Optimization to Support Scientific Decision-making

In this study, a three-dimensional multi-objective optimization model was established to account for the trade-offs among service life, economic cost, and carbon emission reduction. The model was solved using the NSGA-ll algorithm to determine an optimal allocation scheme for steel slag content across different road sections, subject to predefined budgetary and performance constraints. The results demonstrate that a carbon emission reduction potential of approximately 51.3% can be achieved over the planning horizon while maintaining a pavement service life of no less than six years. This enables the synergistic optimization of cost control and carbon mitigation. The proposed model offers a quantitative decision-support framework for the large-scale and refined application of steel slag in pavement engineering. In summary, this study verifies the technical feasibility of applying steel slag to pavement engineering in Xinjiang at the material level and, through environmental system analysis and multi-objective optimization, clarifies its resource recycling potential and regional coordination path under the "dual carbon" goals. The research findings facilitate the transformation of steel slag from solid waste to a low-carbon building material, thereby providing theoretical and empirical support for the green transformation and sustainable development of infrastructure construction in arid-cold regions.

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