



Study on Carbon Emission of Steel Slag Replacing Traditional Sand and Gravel in Road Construction: A case Study of an Expressway in Xinjiang Province

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Abstract. In order to solve the problem of excess steel slag resources and shortage of natural aggregates required for traditional highway construction, several studies have verified the feasibility of using steel slag as pavement aggregate, and related test sections have been laid, which shows that the performance of steel slag pavement is good. This study applies the Life Cycle Assessment (LCA) theory to analyze an engineering case, establishing a carbon emission accounting model and calculating emission reductions achieved by substituting traditional natural sand and gravel with steel slag in highway reconstruction and expansion projects. The carbon mitigation potential of this substitution was further evaluated.

Keywords: Steel slag pavement, Life Cycle Assessment, Energy consumption, Carbon emission.

1 Introduction

In China, Carbon emissions mainly come from sectors such as buildings, electricity, industrial production, and road transportation. Among them, the CO₂ emissions from the transportation sector account for approximately 10% of the total national carbon emissions¹.

At the same time, the utilization rate of steel slag remains low, with most being stockpiled as waste. Current stockpiles exceed 300,000 tons, occupying significant land resources and causing severe environmental pollution². Enhancing steel slag utilization is critical to addressing these challenges. As of 2023, China's crude steel production is 1,019 million tons. Every production of 1 million tons of crude steel will produce 100,000 to 150,000 tons of steel slag³. Most of the use of open storage occupies much

land and the soil, water resources, and air around the landfill, causing pollution. Taking the Wuchang area of Xinjiang as an example, the annual output of steel slag is about 150t, and about 1000t of steel slag has been accumulated, resulting in the tension of the existing deposit site and tremendous environmental pressure. Specific ways and methods are needed to scale up the use of steel slag to alleviate or even solve this problem to the greatest extent. For instance, using electric furnace steel slag as an alternative to crushed stone aggregate and mineral powder in road construction can enhance structural durability while substantially reducing costs⁴. Unlike natural gravel formed through geological processes, steel slag demonstrates superior performance stability, though its application necessitates verification of non-toxicity and volumetric stability. Comprehensive assessments, including heavy metal leaching tests⁵ leachate analysis⁶, and radioactivity evaluations⁷, confirm that steel slag containing trace amounts of hazardous elements poses no toxicological risks to road environments. These findings validate its suitability for pavement base courses and stabilized pavement layers. At the same time, traditional sand and gravel cost more to construct expressways and cause significant harm to the environment in mining and use. According to the survey, gravel aggregate consumption per highway kilometer is 54,000 to 56,000 tons⁸. Due to the severe impact of rock mining on the ecological environment, various departments in 2019-2020 issued guidance documents such as "on promoting the healthy and orderly development of the sand industry" to promote the sustainable development of the sand industry. The lack of natural sand and stone materials, limited mining of mechanical sand and stone raw materials, and no reduction in actual production and construction demand will lead to a sharp rise in sand and stone prices and the production supply chain of road sand and stone materials cannot meet the national development plan. Therefore, the characteristics of the accumulation of steel slag and low price and the limitations of traditional sand and stone in the construction of roads are suitable matches.

Based on this, we will take an expressway in Xinjiang as an example to analyze and quantify the impact of steel slag replacing traditional sand and stone materials in road laying. Thus, the environmental effect brought by the reuse of steel slag is explained from the perspective of carbon emission.

Therefore, this study is an important exploration of the comprehensive utilization of steel slag in the Xinjiang region and even the whole country, and it is a key step in promoting the transportation construction industry in the direction of low carbon, high efficiency, and environmental protection. It will help solve the current environmental challenges and contribute to sustainable economic and social development.

2 Materials and Methods

2.1 Project Profile

As one of the main arteries of the national highway network, Lianhuo Expressway (G30) is an important traffic artery in the national "Belt and Road" Initiative, an important part of the Eurasian Continental Bridge, a middle channel of the three main roads entering and leaving Xinjiang, and a traffic spindle for Xinjiang's economic and

social development. As an important section of G30, the implementation of this project will play an important supporting role in accelerating the construction of the core area of the Silk Road Economic Belt, and it will guarantee social stability and social harmony in Xinjiang. The project starts from G30 Hami North Exit, Yizhou District, Hami City, and ends at Tuyu Gully Interchange, Shanshan County, Turpan City, with a route length of 345.208 km.

The asphalt pavement of the selected section is designed following the "Code for Design of Highway Asphalt Pavement" (JTG D50-2017). The standard axle load is 100KN for a double-wheel group single axle, and in 2026, the opening time after expansion is taken as the characteristic base year. The design service life is 15 years. The main road structure design is considered according to the two types of new road surface and old road surface reconstruction.

Mainline extension pavement structure:

Upper layer: 5cm medium-grained SBS/ rubber powder composite modified asphalt concrete AC-160

Middle surface layer: 7cm medium-grained SBS modified asphalt concrete AC-20C

Bottom layer: 12cm factory heat recovery coarse-grained asphalt gravel ATB-25

Base layer: 36cm5% cement stabilized gravel

Base layer:16cm plant with cold recycled cement stabilized gravel. Total thickness:76cm.

The steel slag in the reconstruction and expansion project of the Hami to Tuyugou section of the G30 Lianhuo Expressway is mainly used in the pavement structure of the central line expansion. In the pavement structure, steel slag is mainly used in the middle surface layer (7cm medium-grained SBS modified asphalt concrete AC-20C) and the base layer (36cm 5% cement stabilized gravel) of the main line expansion pavement structure, and the content of steel slag in it is not less than 30%. In using steel slag in steel slag asphalt concrete, the proportion of steel slag not less than 30% of the total aggregate is appropriate, and the specific proportion in the aggregate should be subject to the test.

2.2 Carbon Emission Accounting Methods

Current studies on carbon emission accounting mainly fall into four categories: IPCC inventory method, actual measurement method, material balance algorithm, model factor decomposition method, and LCA theory. Combining with the current era's mainstream, this project's carbon emission accounting is carried out with the LCA theory.

In the past, Stripple conducted a life cycle assessment of the road construction list section by taking a specific industrial project in Sweden as an example. The computer model adopted in this project is regarded as the first model to apply life cycle to road systems⁹. Qi Yanan et al. applied the Life Cycle Assessment (LCA) theory to clearly define the carbon emission boundary during the construction of expressways¹⁰. Fang Hai et al. guided by the life-cycle theory, constructed a carbon emission calculation model for highway construction period and conducted carbon emission accounting based on the construction project of Panxing Expressway in Guizhou Province¹¹Wu Hao et al. based on actual engineering projects and the theory of life cycle, conducted

research on carbon emissions of individual projects of expressways¹². After years of research, the methods for calculating carbon emissions of highways can be applied by either the competent authorities of the transportation industry or enterprises with responsibility for carbon emission management, including construction units, construction companies, material suppliers or construction machinery suppliers, investment entities, etc¹³.

The carbon emissions activities and sources of highways cover the entire process from raw material production to road operation and maintenance¹⁴, involving multiple stages such as material physicalization, construction and construction work, operation and maintenance, and demolition and waste disposal¹⁵, as well as different types of emissions. Currently, only the carbon emissions of main materials and high-energy-consuming equipment during the construction process of highways are considered in the material physicalization stage¹⁶.

Therefore, based on the LCA principle, the waste or greenhouse gases emitted in the product's production process are measured, and the burden of these wastes or greenhouse gases on the environment is assessed to propose targeted measures to improve the environment. The highway pavement construction process will consume energy and resources and output a large amount of carbon dioxide, so LCA theory can calculate the carbon emissions in the pavement construction process to achieve the purpose of life cycle evaluation.

(1) Functional Unit and System Boundary Clarification

The functional unit for this study is defined as "the carbon emissions per kilometer of expressway pavement construction using steel slag as a partial substitute for traditional aggregates." This unit enables direct comparison with conventional road construction practices. The system boundary follows a cradle-to-gate approach, covering:

Raw Material Production Phase:

Includes emissions from traditional aggregate mining, crushing, and screening. Steel slag, as an industrial by-product, is allocated zero upstream emissions via the zero-burden method.

Material Transportation Phase:

The analysis quantifies diesel fuel consumption and associated emissions during the 275-km road transportation of steel slag from Xinjiang Bayi Steel Plant (production origin) to the Tuyugou construction site. Transportation parameters account for typical heavy-duty truck operational characteristics.

Construction Phase:

Emission calculations encompass energy consumption from construction equipment operations including:

Excavation and material handling (utilizing medium-duty silt removers)

Landfill placement operations (via wheeled loaders)

Compaction processes (employing vibratory tampers)

End-of-Life Considerations:

- Operational Phase Exclusion: The 15-year service life operational emissions are excluded from system boundaries, aligning with the study's focus on construction-phase mitigation potential.

- Demolition Phase Exclusion: Post-demolition emissions are omitted due to two key factors:
 - a) Demonstrated high material stability of steel slag in pavement applications
 - b) Technical feasibility of material recycling at end-of-life
 - c) Current limitations in reliable demolition-phase data availability

2.3 Assumptions and Their Impact Discussion

In academic inquiry, the explicit formulation of research hypotheses serves as a critical bridge between theoretical construction and empirical verification. This process assumes particular significance in interdisciplinary investigations or when addressing phenomena characterized by complex variable interdependencies, where preliminary hypothesis articulation may generate divergent interpretative pathways. Our methodological approach incorporates a structured hypothesis refinement phase for two principal reasons: primarily, to account for potential contextual mediation of variable interactions; and secondarily, to establish precise boundary parameters for the experimental design. Through systematic conceptual clarification, this framework not only resolves terminological ambiguities but more crucially enables the development of empirically testable theoretical propositions. This section provides critical examination of the underlying theoretical presumption and its methodological ramifications, establishing causal linkages between assumption validation and subsequent analytical outcomes through systematic scrutiny.

Our analytical framework specifically excludes upstream steel production emissions (encompassing slag generation processes) when evaluating zero-emission allocation strategies for steel slag residues. The methodological paradigm explicitly assigns full environmental liability to primary steel manufacturing facilities through rigorous system boundary definition. Although this methodological choice introduces a potential downward bias in cumulative emission estimates, it maintains methodological alignment with established industrial accounting protocols for secondary material valuation.

Secondly, the methodological framework operationalizes diesel truck transportation efficiency through prescribed optimal fuel consumption parameters (25 L/100 km baseline) within life-cycle inventory analysis. Notwithstanding this operationalization, inherent system variabilities—including traffic flow stochasticity and vehicular maintenance irregularities—may induce non-linear escalations in actualized fuel demand, consequently necessitating upward adjustments in associated mobile source emission factors.

Thirdly, the methodological exclusion of operational phase emissions creates an analytical bias that prioritizes construction-phase emission mitigation while potentially discounting the material longevity advantages inherent to steel slag applications. Specifically, this system boundary demarcation may systematically undervalue life-cycle emission differentials through neglect of maintenance emission abatement mechanisms enabled by enhanced durability parameters.

Fourthly, the analytical protocol presumes physicochemical integrity of stabilized steel slag matrices under prescribed environmental conditions, with expansion coefficient variability and leaching potentials maintained below critical thresholds through

system boundary delineation. Notwithstanding this foundational premise, emergent matrix destabilization phenomena—should they manifest—could induce secondary emission pathways during remediation interventions, thereby constituting a critical pathway for environmental performance degradation that potentially countervails initial carbon sequestration benefits.

3 Results & Discussion

3.1 Carbon Emission Accounting at Each Stage

Under the above concept and construction design, the content of steel slag in each surface layer is obtained, as shown in the table 1

Table 1. Content of steel slag of each surface layer

Location	Steel slag content (m ³)
Base layer	2231.2152
Middle surface layer	798.51
Leveling layer	52.023
Total amount	3081.7482

(1) Carbon emission accounting at the material production stage

Since steel slag is the waste after steel produced by steel mills, the carbon emission of steel slag in the production stage of building materials is zero, and it does not participate in the carbon emission in the construction process of highway pavement. Therefore, the carbon emissions accounting of the steel slag can only be calculated from the carbon emissions released by using mechanical equipment in the transportation stage of building materials and the construction process.

(2) Carbon emissions accounting in the material transportation stage

Raw steel slag must be transported from production sites to construction sites, with carbon emissions in this stage primarily attributed to vehicle fuel consumption. There are four main modes of transport for goods in our country: railway, road, water and air transport. Different modes of transportation consume different amounts of carbon dioxide. For most projects, the road is chosen as the mode of transportation after considering the economic and environmental factors. In our country, most trucks use diesel as fuel, and this paper assumes that diesel is used. In the process of road construction materials from the production place to transport to the construction point, the type of transport machinery is different, the type of transport is different, the weight or volume of transport is different, the number of different shifts leads to the fuel used in the transport process is different, in the calculation of transport stage emissions, should be considered comprehensively in the transport process of the impact factor, the amount of fuel used multiplied by the use of fuel Material corresponding to the carbon emission factor, the sum of fuel carbon emissions of all transportation machinery for the material transportation stage carbon emissions, namely

$$E_{\text{transportation}} = \sum_{d=i}^m \sum_{i=1}^n (N_{di} \times D_{di} \times S_d \times \lambda_d \times W_i) \tag{1}$$

Where: E transportation represents the carbon emissions generated in the process of mechanical transportation of materials, i represents the d type of transportation machinery, i represents the type of transportation materials, N_{di} represents the transport machinery d transport unit weight or volume material i consumed in every kilometer of the shift, D_{di} represents the transport machinery d transport unit weight or volume material i distance, S_d represents the transport machinery d fuel consumption per shift, λ_d represents the transport machinery d fuel used by the corresponding CO₂ emission factor, w_i represents the weight or volume of the transport material i.

This paper will take Baosteel Group Xinjiang Bayi Iron and Steel Co., Ltd. as the starting point for calculating carbon emissions in the material transportation stage and Tuyu Valley as the calculation endpoint of the material transportation stage, with a total length of 275km. Now, it is known that this project needs to transport 3081.7482m³ of steel slag to the Tuyugou area, and plans to put 205 diesel dump trucks within 15t, with a fuel consumption of 25L per 100 kilometers. (Equipment fuel consumption rates and the data in Table Three are derived from manufacturer specifications and field measurements in similar projects.)

According to the "Guidelines for the Compilation of Provincial Greenhouse Gas Inventories in China" and "Baseline Emission Factors for China's Regional Power Grids", the primary energy carbon emission factors are shown in Table 2.

Table 2. Main energy emission factors

Energy type	Carbon emission factor /kgCO ₂ eq
Electricity/KWH	0.93
Energy type	Carbon emission factor /kgCO ₂ eq
Gasoline /t	2.93
Heavy oil /t	3.06
Diesel /t	3.10

Therefore, the fuel consumption of the dump truck in a single transport process is 68.75 liters, and the carbon emission is 68.75×3.10= 213.125 (kgCO₂eq).

Then, the carbon emissions in the material transportation stage =213.125×205=43690.625 (kgCO₂eq)

(3) Carbon emission accounting in road construction stage

Different construction machinery on the construction site will produce different fuel consumption. When calculating the carbon emissions in the construction stage, the different mechanical usage in the construction process is converted into fuel consumption and multiplied by the carbon emission factor corresponding to fuel use. The carbon emissions in the construction stage are the sum of the fuel carbon emissions of all construction machinery, that is

$$E_{construction} = \sum_{j=1}^p (N_j \times F_j \times \lambda_j) \quad (2)$$

In the formula: $E_{construction}$ represents the carbon emissions generated by construction machinery in the construction process, j represents the j type of construction machinery, N_j represents the amount of construction machinery, F_j represents the fuel consumption of each class of construction machinery j , λ_j represents the CO_2 emission factor corresponding to the fuel used by construction machinery j .

Considering the power performance of diesel, this pilot project is stable, has a high fuel economy, and has a strong reliable durability and storage, so diesel is the primary source of construction equipment energy (Table 2 for the main energy carbon emission factors). In addition, the construction process involved in steel slag mainly has three stages: excavation, landfill compaction, and the construction instruments used in each stage and their work efficiency are not the same. Table 3 shows the equipment used in the three stages of excavation landfill and compaction, and the work efficiency of the instruments.

Table 3. Construction instruments at each stage

Construction Stages	Construction equipment	Work efficiency	Fuel consumption (L/h)	Number of units	Carbon emission factor (diesel)
Excavation	Medium dredger	150m ³ /h	15	5	3.10 kgCO ₂ eq
Landfill	Medium tire forklift	75m ³ /h	13	5	
Compaction	Vibratory tamper	400m ³ /h	1	1	

According to the above calculation, the total steel slag used in pavement engineering is 3081.7482m³. Now assume that all the steel slag is buried in a layer every 0.3 m (17.12 layers) to a pit of 20*30*10.136 cubic meters. Among them, 5 meters in 10.136 meters are protective measures to prevent dust and leachate pollution. Therefore, carbon emissions from excavation, landfill, and compaction are shown in Table 4.

Table 4. Summary of carbon emissions from excavation, landfill, and compaction

	Excavation	Landfill	Compaction
Carbon emissions (kgCO ₂ eq)	1824.3	3267.8464	47.12

To sum up, in the entire construction activities related to steel slag, the carbon emissions generated by construction machinery during the construction process $E=1824.3+3267.8464+47.12=5139.2664$ (kgCO₂eq)

3.2 Carbon Sensitivity Analysis

This case analysis quantifies carbon emissions based on fixed steel slag content; however, it does not fully capture the varying impacts of different steel slag quantities on emission levels. Therefore, we will adjust the content of steel slag and calculate the carbon emission to conduct a sensitivity analysis.

First of all, when we only allow the amount of steel slag for the corresponding pavement structure to be reduced to 5%, the total amount of steel slag is shown in Table 5:

Table 5. The amount of steel slag for each pavement layer (5% of steel slag)

Location	Steel slag content (m ³)
Base layer	371.8656
Middle surface layer	133.08
Leveling layer	8.67
Total amount	513.6156

Similarly, we get the amount of steel slag in different contents, as shown in Table 6.

Table 6. Actual slag content under different percentages content of steel slag

Percentage of steel slag content	Actual steel slag content (m ³)
5%	513.6156
10%	1027.2412
15%	1540.8568
20%	2054.4824
25%	2568.0980
30%	3081.7482
35%	3595.3492
40%	3595.3492
45%	4108.9648
50%	5136.196

Therefore, according to the previous calculation of carbon emissions, we can get the carbon emissions under different steel slag content, as shown in Figure 1.

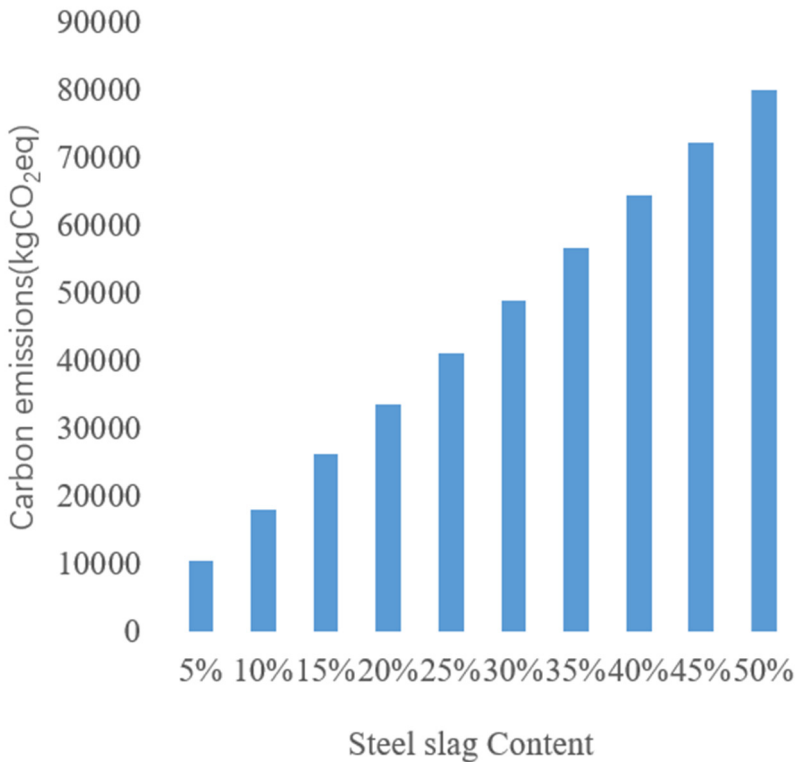


Fig. 1. Carbon emissions under different steel slag percentage content

Currently, it is well established that when the proportion of steel slag ranges from 5% to 30%, there is a clear relationship between its usage and carbon emissions. Consequently, in cases where steel slag is not utilized as a substitute for traditional sand and gravel materials in construction, the calculated volume of sand and gravel materials required is 10,256.55 m³. According to the Life Cycle Assessment (LCA) theory, the carbon emissions for each stage are presented in Table 7.

Table 7. The carbon emissions from the construction of traditional sand and gravel materials

	Material processing	Transportation and landfill
Carbon emissions (kgCO ₂ eq)	31806.80	162766.30
In total	194573.11 kgCO ₂ eq	

Therefore, according to the traditional sand and gravel materials calculation of carbon emissions, we can get the carbon emissions reduction under different steel slag content, as shown in Figure 2.

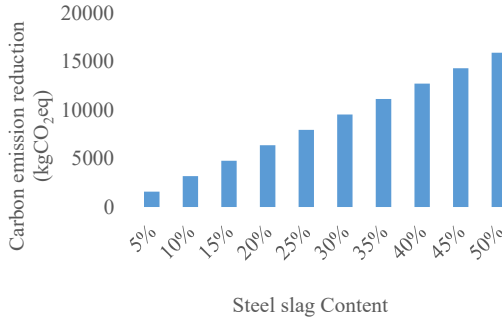


Fig. 2. Carbon emission reduction under different steel slag percentage content

The data found that when the steel slag pavement structure, the steel slag content accounted for more and more its carbon emission reduction trend, mainly because when the amount of steel slag increased, the original gravel material in its processing stage of the workload is reduced, the carbon emissions of processing equipment will also be reduced. The processing stage of the gravel has the highest proportion of carbon emissions in its entire life cycle. Therefore, to a certain extent, properly controlling steel slag's content can reduce carbon emissions.

3.3 Summary of This Chapter

By calculation, the total life cycle carbon emission of the road construction of the case project E=48829.8914 kgCO₂eq;

The carbon emission data of the whole life cycle of pavement construction and the carbon emission data of each stage of pavement construction show that the carbon emission released in the material transportation stage of the whole life cycle of pavement construction accounts for the most significant proportion, followed by the road construction stage; In the production stage, because the steel slag is the waste after the steel produced by the steel mill, the carbon emissions of the steel slag in the production stage of the building materials are zero. This also shows that steel slag, as a substitute for traditional sand and stone, is effective in reducing carbon emissions and alleviating the pressure of steel slag accumulation.

In addition, This transportation stage from the road construction life cycle carbon emission data and the analysis of carbon emission data of each stage of road construction can show that the road construction life cycle transport distance has a more significant impact on the CO₂ emissions of road construction output, the longer the transport distance, the more significant the proportion of CO₂ emissions, in the material transportation stage, long-distance transport machinery for CO₂ emissions compared to the central role The carbon emissions of loading machinery are only related to their power.

Therefore, it is suggested that new energy vehicles or equipment should be selected as a priority for operation, transport distance should be reduced, and a low-carbon construction organization plan should be adopted for flexible deployment to improve transport efficiency. Meanwhile, during the construction process, ecological restoration is concurrently implemented on the temporary construction land. This enables the surrounding green spaces to also achieve a certain amount of carbon sequestration. According to relevant data statistics, the annual carbon sequestration capacity of each hectare of green space can reach 10-15 tons.¹⁷

Regarding sensitivity analysis, the data shows that when the content of steel slag in the pavement structure increases, its carbon emission reduction trend increases. This is mainly because when the amount of steel slag is increased, the workload of the original gravel material in its processing stage is reduced, and the carbon emission of processing equipment is also reduced. Furthermore, the processing stage of the gravel has the highest proportion of carbon emissions in its entire life cycle. Therefore, to a certain extent, properly controlling steel slag's content can reduce carbon emissions.

4 Conclusions

This study focuses on the comprehensive utilization of steel slag in pavement engineering in Xinjiang region and has achieved a series of important results through the exploration of carbon emission.

Carbon emission accounting and emission reduction studies found that steel slag utilization can effectively reduce carbon emissions. Taking a road project in Xinjiang as an example, through the whole life cycle theory and carbon emission factor method calculation, the carbon emission of steel slag in the material production stage is zero, and the carbon emission in the transportation and construction stage is lower than that of traditional crushed stone. And the higher the steel slag content, the more carbon emission reduction. This indicates that steel slag, as a substitute for traditional sand and stone, significantly reduces carbon emissions and alleviates the accumulation pressure of steel slag.

In conclusion, integrating steel slag in road construction in Xinjiang demonstrates technical feasibility, environmental benefits, and economic viability. In the future, we should further strengthen the research and development and promotion of comprehensive utilization technology of steel slag, improve relevant policies and regulations, promote the coordinated development of the steel industry and transportation construction industry, and provide strong support for realizing the sustainable development of transportation construction in Xinjiang and even the whole country.

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