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Research on Low-carbon Construction Technology for Municipal Road Projects and Carbon Emission Calculation

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Abstract: Against the backdrop of the "Dual-Carbon" goals, municipal road projects constitute a key component of urban infrastructure construction, and carbon emissions during their construction phase have attracted growing attention. This paper briefly analyzes the composition of carbon emissions and the value of low-carbon construction for municipal road projects. It also discusses practical dilemmas faced by low-carbon construction and carbon emission calculation, as well as construction technical pathways and calculation optimization strategies. The paper is expected to provide referential ideas for the practical application of low-carbon construction and carbon emission control in municipal road projects, and promote the green and low-carbon transformation of municipal infrastructure construction.

Keywords: Municipal road; Low-carbon construction; Carbon emission calculation

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1. Introduction

Municipal road projects form the backbone of urban infrastructure. A large number of roads are newly built or reconstructed every year. Construction consumes massive amounts of building materials and energy, generating considerable carbon emissions that cannot be overlooked. Municipal road projects feature large-scale investment, long construction periods, numerous participating entities, and close ties with urban operations. Carbon emissions stem not only from the production and transportation of building materials, but also from energy consumption of construction machinery, on-site operation organization, waste disposal, and many other aspects. Taking the construction phase of municipal road projects as the research object, this paper provides a theoretical basis and references for the green and low-carbon development of the municipal road industry from two perspectives: application pathways of low-carbon construction technologies and simplified methods for carbon emission calculation.

2. Composition of carbon emissions and value of low-carbon construction for municipal road projects

2.1. Main sources of carbon emissions from municipal road projects

Carbon emissions of municipal road projects run through the whole life cycle of a project. Nevertheless, carbon emissions in the construction phase represent a critical link that can be regulated through technical and managerial measures throughout the full life cycle. According to emission sources, carbon emissions can be divided into three categories: embodied carbon emissions from building materials, carbon emissions from energy consumption of construction machinery, and indirect carbon emissions from on-site operations. Embodied carbon emissions from building materials constitute the largest component of carbon emissions for municipal roads [1]. Asphalt mixtures, cement concrete, steel products, sand and gravel aggregates are the principal building materials for road projects. Their production consumes huge quantities of energy, and the resulting carbon emissions dominate total carbon emissions of road projects. Embodied carbon emissions from asphalt surface layers and base materials of urban arterial roads generally account for the majority of total project carbon emissions. Carbon emissions from construction machinery energy consumption mainly originate from the operation of fuel-powered equipment such as rollers, pavers, excavators, loaders, and transport vehicles. Municipal road construction sites are compact with frequent mechanical operations. Restricted by urban traffic control, transport vehicles have to take detours or idle while waiting, which increases fuel consumption and carbon emissions [2]. Indirect carbon emissions from on-site operations include electricity consumption for temporary construction facilities, transportation and disposal of construction waste, and commuting of construction personnel. Though each individual item accounts for a small proportion, their cumulative impact is substantial for projects with long construction periods.

2.2. Core value and internal mechanism of low-carbon construction technologies

The essence of low-carbon construction technologies lies in reducing energy consumption and waste generation during construction via technical replacement, process improvement, and management optimization, on the premise of guaranteeing road service functions and durability, so as to achieve carbon emission reduction. In terms of material substitution, replacing natural building materials with industrial waste or recycled materials can, on the one hand, cut carbon emissions generated in the production of new materials, and on the other hand, realize resource-based utilization of waste. Reusing Reclaimed Asphalt Pavement (RAP) materials for surface paving can significantly reduce the consumption of new asphalt and sand-gravel aggregates [3]. In terms of process optimization, improving construction techniques can lower energy consumption. In terms of management upgrading, scientifically formulated construction organization designs reduce mechanical idling, optimize transport route arrangements, and shorten construction schedules, thereby indirectly curbing carbon emissions.

3. Practical dilemmas of low-carbon construction and carbon emission calculation

3.1. Imperfect carbon emission calculation system

Calculation boundaries, emission factors, and data sources adopted in different research and practical practices vary to some extent, leading to poor comparability of calculation results [4]. Some studies only calculate carbon emissions from building-material production; some include construction machinery and transportation links; others incorporate carbon emissions from road operation phases. Divergent project

boundary definitions prevent horizontal comparison and hinder government departments from formulating targeted carbon reduction goals [5]. Furthermore, mainstream calculation methods impose high requirements on the completeness of basic data. Scattered data, such as on-site energy consumption and transportation of small-batch building materials, are difficult to collect. Many small- and medium-sized construction enterprises lack complete statistical systems, making refined carbon-emission accounting difficult and impeding the promotion and implementation of low-carbon construction technologies.

3.2. Unbalanced application of low-carbon technologies

In terms of technology types, relatively mature technologies such as warm-mix asphalt and recycled mixtures see high application rates in large- and medium-sized cities, yet low utilization in small- and medium-sized cities and county-level road projects. In terms of project types, key demonstration projects actively adopt new technologies, while ordinary maintenance and repair projects mostly stick to traditional maintenance techniques. In addition, application costs constitute a major constraint for popularization [6]. Certain low-carbon technologies require high initial investment; for instance, large investment is needed for recycled pavement equipment, which is unaffordable for small- and medium-sized enterprises. Meanwhile, some construction entities' understanding of low-carbon construction remains confined to environmental protection requirements. They fail to fully recognize its comprehensive value in cost reduction, efficiency improvement, and long-term emission abatement. They hold a conservative attitude toward new technologies and tend to adopt proven traditional construction processes to avoid potential management and quality risks brought by new technology adoption.

3.3. Insufficient policy incentives and market mechanisms

Although the state has put forward the "Dual-Carbon" goals and relevant green building policies, specific carbon reduction targets, subsidy policies, and assessment mechanisms for municipal road projects have not been refined and implemented. Substantial support is lacking for construction enterprises that adopt low-carbon technologies and conduct carbon emission accounting. Existing policies are mostly macro-level guiding opinions, without supporting incentives such as fiscal subsidies and tax relief. They cannot offset the increased initial costs of low-carbon technologies and fail to effectively motivate construction enterprises to take initiative in transformation [7]. From the market perspective, the carbon emission trading market currently mainly covers industries including power, steel, and building materials. The municipal road construction sector has not been incorporated into trading coverage. Carbon reduction benefits generated by construction enterprises cannot be converted into real economic gains through market transactions, further weakening enterprises' motivation for low-carbon transformation.

4. Technical pathways for low-carbon construction and optimization strategies for carbon emission calculation of municipal road projects

4.1. Application pathways of key low-carbon construction technologies

To promote the application of low-carbon construction technologies for municipal roads, construction technologies with high technical maturity, prominent carbon reduction effects, and reasonable economic value shall be prioritized according to project characteristics and local resource conditions. Warm mix asphalt technology ranks among the low-carbon construction technologies with great promotion prospects at

present [8]. Without altering the gradation and road performance of asphalt mixtures, this technology achieves energy conservation and carbon reduction by lowering mixing and compaction temperatures. During urban road construction, warm-mix asphalt can also extend the construction season, reduce flue gas emissions, and improve working conditions. Taking an urban expressway reconstruction and expansion project as the research object, warm mix asphalt mixtures were adopted for the upper surface layer along the whole route. Compared with traditional hot mix processes, fuel consumption was reduced by approximately 18%, flue gas emissions decreased, and working conditions for construction workers were markedly improved. Recycling of pavement materials constitutes a suitable technology for road overhaul, reconstruction, and expansion projects. Asphalt materials from old subgrades and pavements are crushed and screened, then blended into new mixtures to repave pavement structural layers, which cuts the quantity of newly mixed asphalt and sand-gravel materials. The blending proportion of RAP shall be determined via tests according to old material performance and road grade. For upper surface layers of urban arterial roads, RAP content is generally controlled within 20%–30%, and the proportion can be appropriately raised for lower surface layers and base courses. A reconstruction and expansion project of an urban arterial road adopted plant-mixed hot-recycling technology with RAP content exceeding 35%. The consumption of new materials per kilometer of pavement decreased by about 400 tons, and embodied carbon emissions were reduced by one-third owing to this technology [8]. Besides, prefabricated construction technologies boast broad application prospects for municipal auxiliary works. Components such as curbstones, rainwater inlets, drainage ditches, and sidewalk slabs are prefabricated in factories and installed on-site. This reduces formwork and curing energy consumption caused by on-site casting, accelerates construction progress, and ensures stable construction quality [10]. For example, full adoption of prefabricated sidewalk slabs in a sidewalk renovation project shortened on-site construction duration by nearly 30%, helped cut waste-related carbon emissions from on-site cement mixing, and achieved favorable comprehensive benefits.

4.2. Simplification and practical implementation of carbon emission calculation methods

Given the current complexity of carbon emission calculation and difficulties in data collection, promoting simple and effective calculation tools facilitates practical operation. Instead of building complex mathematical models, construction enterprises can obtain total project carbon emissions by separately counting energy and material consumption by construction activity category and multiplying corresponding emission factors. The key to simplified calculation lies in establishing an emission factor library and activity data collection list suitable for municipal road projects [11]. For emission factors, general values released by national or industrial authorities shall be prioritized, and local field measurements shall be gradually carried out in qualified regions. For activity data, construction enterprises may add carbon emission statistical dimensions based on daily material ledgers and machinery refueling records without massive additional manpower input.

Table 1. Examples of application for simplified carbon emission calculation method for municipal road construction

Calculation Link	Data Source	Reference Emission Factor Value	Application Example
Asphalt Mixture		Take industry average values by material type	An engineering project consumes 8000 tons of asphalt surface layer material. Look up unit embodied carbon emissions from the factor table and multiply to get total volume.

Cement Concrete	Ready-mixed Concrete Delivery Note	Adopt corresponding factors by strength grade	A project uses 5000 cubic meters of C30 concrete. Multiply by the unit factor to obtain building material carbon emissions.
Construction machinery Fuel Consumption	Machinery Refueling Records	Separate factors for diesel and gasoline	Count total diesel consumption over the project period and multiply by the diesel carbon emission factor to get machinery energy consumption emissions.
Transport Vehicles	Transport Ledgers or GPS Data	Adopt factors by ton-kilometer	Count total ton-kilometers of material transportation and multiply by unit transport emission factor.

In practical application, construction enterprises may start with major links, focus on counting the largest carbon emission sources such as building material and fuel consumption, and gradually supplement carbon emission data of other links. Calculation results can be used not only for evaluating internal carbon reduction performance of projects, but also as low-carbon performance data submitted to project owners and government departments. Qualified enterprises may combine carbon emission calculation with construction schedules. Differences in carbon emissions among alternative construction schemes shall be considered during scheme comparison and selection, so as to realize source-oriented carbon emission control [12].

4.3. Management guarantees and policy suggestions

The promotion of low-carbon construction technologies and practical implementation of carbon emission calculation both require sound management systems and policy environments.

Establishing a standard guiding system constitutes an urgent priority. Competent industrial authorities shall accelerate the formulation of technical guidelines for low-carbon construction and carbon emission calculation standards for municipal road projects, define calculation boundaries, methods for determining emission factor values and data collection requirements, and provide operable technical foundations for enterprises. Research and formulation of evaluation standards for low-carbon municipal road projects may also be carried out, and carbon emission indicators shall be incorporated into reviews for green construction sites and high-quality projects [13].

Improving incentive restraint mechanisms is the key focus. Projects adopting low-carbon construction technologies with carbon emission intensity below industrial average levels shall receive preferential treatment in bidding, credit evaluation, merit selection, and other dimensions. Regions with sufficient conditions may set up special subsidies for low-carbon construction to offer certain cost support for small- and medium-sized enterprises in the initial stage of low-carbon technology adoption. In the long run, municipal road construction shall be incorporated into the coverage of carbon emission right trading or carbon reduction support instruments, so that carbon reduction actions can yield real economic returns [14].

Strengthening technical training and talent cultivation serves as fundamental support. Managers and operators of construction entities shall understand and be capable of operating low-carbon construction technologies to realize low-carbon construction goals. Vocational colleges and industrial associations may jointly develop relevant vocational education and practical programs to deliver high-skilled talents with engineering expertise and low-carbon awareness to society [15].

Giving play to the leading role of project owners is also of great importance. Owners shall clarify low-carbon construction requirements in project planning and tendering phases, specify carbon emission-control targets in bidding documents and contract clauses, and compel construction enterprises to voluntarily adopt low-carbon technologies. Government-invested municipal road projects shall set an exemplary precedent.

5. Conclusion

Major sources of carbon emissions during municipal road construction are embodied carbon emissions from building materials and energy consumption of construction machinery. Together they account for over 80 % of total emissions and become core targets for carbon-reduction work. Low-carbon construction technologies deliver carbon reduction effects through three approaches: material substitution, process improvement, and management upgrading. Technologies including warm-mix asphalt, recycled pavement materials, and prefabricated construction have seen relatively mature application and achieved notable carbon reduction outcomes. The simplified carbon emission calculation method proposed in this paper is based on inventory statistics and supported by commonly available data sources. It does not require complex models and can be implemented in the daily management of construction enterprises. With accumulated data and technological advancement, carbon emission calculation will grow increasingly accurate, and the carbon reduction potential of low-carbon construction technologies will be further unlocked. Promoting low-carbon transformation in the municipal road industry is an inevitable choice in response to the national "Dual-Carbon" strategy and an inherent demand for enhancing the industry's capacity for sustainable development.

Disclosure statement

The author declares no conflict of interest.

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