Proceedings of the Transportation Research Congress 2025

July 20-23, 2025

Beijing International Convention Center, Beijing, China

https://www.trc-c.org/

Contents

Overview

The Transportation Research Congress 2025 brought together over 300 experts and scholars from China, the United States, the United Kingdom, the Netherlands, and several other countries and regions. Centered on the theme of "Sustainable, Resilient, and Smart Future Transportation," the congress covered a broad range of topics including highways, railways, airports, traffic management, and intelligent driving.

The program featured 9 keynote speeches, 36 parallel sessions, 1 roundtable discussion, and 2 international expert review forums for graduate students. Discussions highlighted that the integration of artificial intelligence, big data, and new material technologies will be essential to developing more efficient, safer, and environmentally friendly transportation systems worldwide.

As a key milestone in the TRC series, TRC2025 not only showcased the latest advances in transportation science and technology but also reinforced interdisciplinary and international collaboration. It made significant contributions to promoting innovation across the field and accelerating the development of future transportation.

Looking ahead, TRC2027 will be hosted by Tongji University in Shanghai, where delegates look forward to reconvening in two years to further drive progress in transportation innovation.

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- ✧ Kang Zhao, Liaoning University of Technology, Assistant Professor
- ✧ Qian Zhao, China Railway Design Corporation, Postdoctoral Research Fellow
- ✧ Zhengfeng Zhou, Southwest Jiaotong University, Professor

Opening Ceremony

Moderator: Yinghao Miao, Professor, University of Science and Technology Beijing

Welcome Speech
Renshu Yang, Professor, President, University of Science and Technology Beijing
Introduction of the National Center for Materials Service Safety (NCMS)
Xiaolu Pang, Professor, Director of NCMS, University of Science and Technology Beijing
Introduction of TRC
Linbing Wang, Professor, University of Georgia

Plenary Session 1

Moderator: Baoshan Huang, Edwin G. Burdette Professor, The University of Tennessee, Knoxville;Ya Wei, Professor, Tsinghua University

Keynote Speech: Decarbonising Road Freight
David Cebon, Professor, Fellow of the Royal Academy of Engineering, University of Cambridge
Keynote Speech: New Idea for Long Life Pavement Design
Lijun Sun, Professor, Tongji University

Plenary Session 2

Moderator: Chunsheng Cai, Professor, Southeast University; Danhui Dan, Professor, Tongji University

Keynote Speech: 3D Printing Oriented New Construction Technology, Material, and Structure
Guowei Ma, Professor, Vice President, Hebei University of Technology
Keynote Speech: Dynamics of Airport Runway System and Its Application
Jianming Ling, Professor, Dean of the College of Transportation, Tongji University
Keynote Speech: Active Prevention and Control Technology for Road Ices and Snow Disasters
Yiqiu Tan, Professor, President of Harbin Institute of Technology, Weihai, Harbin Institute of Technology

Plenary Session 3

Moderator: Yanjun Qiu, Professor, Southwest Jiaotong University; Yuhong Wang, Professor, The Hong Kong Polytechnic University

Keynote Speech: Discussion & Practice on Several lssues in Intelligent Tunneling
Hehua Zhu, Professor, Academician of the Chinese Academy of Engineering, Tongji University
Keynote Speech: Recycling Applications in Asphalt Pavements
Baoshan Huang, Edwin G. Burdette Professor, The University of Tennessee, Knoxville

Plenary Session 4

Moderator: Wenqi Ding, Professor, Tongji University；Xueyan Liu, Delft University of Technology, Associate Professor

Keynote Speech: Research Prospects and Reflections toward Intelligent Bridges
Chunsheng Cai, Professor, Southeast University
Keynote Speech: Multiscale Simulative Testing for Performance and Fundamental Properties of Asphalt Pavements and Materials
Linbing Wang, Professor, University of Georgia

Plenary Session 5

Moderator: Linbing Wang, Professor, University of Georgia; Yiqiu Tan, Professor, President of Harbin Institute of Technology, Weihai, Harbin Institute of Technology

Lifetime Achievement Award Ceremony

Panel Discussion: Future Transportation

Plenary Session 6

Moderator: Linbing Wang, Professor, University of Georgia

Welcome from the Next TRC

Parallel Session A1

Topic: High-Performance Materials and Innovative Structural Technologies for Underground Engineering Applications

Chair: Peng Feng, Professor, Tsinghua University; Wenqi Ding, Professor, Tongji University; Xinmiao Meng, lecturer, Beijing Forestry University; Qing Chen, Professor, Tongji University

Speech:

Progress in Technology and Application of Fiber-Reinforced Polymer Composite Materials for Underground Engineering Structures

Peng Feng, Professor, Tsinghua University

Enhancing Load-Bearing Capacity of Shield Tunnels with Fiber-Reinforced Polymers

Hai Fang, Professor, Nanjing Tech University

New Supporting Technology, Theory and Computational Method of Corrugated Steel for Tunnels

Wenqi Ding, Professor, Tongji University

Multi-scale Simulation and Regulation of UHPC Material Properties

Qing Chen, Professor, Tongji University

Experimental Investigation of Coal Gangue Aggregate Concrete Confined by FRP

Jiaqi Yang, Associate Professor, China University of Mining and Technology (Beijing)

Parallel Session A2

Topic: Basic Theory of Resilience of Deep Underground Space in Mega-Cities

Chari: Dong Su, Professor, Shenzhen University; Yafei Qiao, Associate Professor, Tongji University; Chao Zhang, Professor, Hunan University; Mingyang Wang, Professor, Tsinghua University

Speech:

Interaction Mechanisms and Control Strategies for Soil-Bentonite-Water Systems in Subaqueous Large-Diameter Shield Tunnels

Dalong Jin, Associate Professor, Beijing Jiaotong University

Evolution of Dynamic Axial Compression Ratio and Seismic Behavior of Central Columns in Subway Stations

Peng Deng, Professor, Hunan University

Mechanics/Resilience- Intelligence-Carbon Study of Prefabricated Underground Structures

Tong Qiu, Distinguished Researcher, Shenzhen University

Mechanical Response of Cross-Fault Tunnels under Faulting

Yafei Qiao, Professor, Tongji University

Damage Assessment of Tunnel Segmental Linings under Internal Explosion Scenarios: A Simplified Approach

Omer Javaid, Postdoc, Shenzhen University

Parallel Session B1

Topic: Key Technologies for Emergency Repair and Rapid Traffic Resumption in Railway Infrastructure

Chair: Xianfeng Liu, Professor, Southwest Jiaotong University
Cochair: Hui Li, Professor/Changjiang Scholar, Tongji University
Introduction:

China's highway and railway network has achieved remarkable scale, with total mileage exceeding 5.5 million kilometers, ranking first globally and representing a critical component of the nation's infrastructure backbone. This extensive transportation network spans diverse topographic and geomorphological units, traversing mountainous regions, plains, deserts, and coastal areas, while operating within complex disaster-prone environments characterized by varied geological conditions and climatic zones. The network faces persistent threats from frequent natural disasters, including mountain floods, debris flows, landslides, earthquakes, and extreme weather events that occur regularly along transportation corridors. Different road segments exhibit distinctly varying disaster development backgrounds, spatial distribution patterns, temporal activity characteristics, and destructive capacities, resulting in complex and multifaceted disaster mechanisms that significantly complicate risk assessment and hazard prediction. These complexities create substantial challenges for effective disaster detection, monitoring, and early warning systems. Furthermore, the current lack of systematic and integrated post-disaster emergency repair decision-making frameworks, coupled with insufficient repair efficiency and limited technological capabilities, severely impede emergency rescue operations and disaster response efforts. This situation poses serious and escalating threats to public safety, economic stability, and overall transportation security, potentially disrupting critical supply chains and emergency services. Consequently, there is an urgent and pressing need to develop comprehensive emergency repair and rapid restoration technologies specifically designed for long-distance linear transportation infrastructure, incorporating advanced materials, intelligent monitoring systems, and automated repair mechanisms to substantially enhance China's post-disaster emergency repair and restoration capabilities for transportation infrastructure while ensuring resilient and sustainable network operations.

Speech:

Geological Hazards: Data, Mechanisms, Technologies, and Applications
Chong Xu, Naional Institute of Natural Hazards,Ministry of Emergency Management of China

Key Technologies for Digital Intelligence-Empowered Resilience Enhancement of Highways
Ning Xie, China Academy of Information and Communications Technology

Tornado-induced Risk Analysis of Railway System Considering the Correlation of Parameters

Cheng Yang, College of Civil Engineering.Southwest Jiaotong University

基于大型土工离心机试验的极端降雨诱发在役公路路基滑坡灾害机理研究

黄雨，罗森林，朱崇强, College of Civil Engineering, Tongji University

Ecology and Resilience of Transportation Infrastructure: Theory and Practice

Hui Li, College of Transportation, Tongji University,

Design theory and method of high performance cement-based materials for improving traffic facility resilience

Cong Ma, Guangdong Province Key Laboratory of Durability for Marine Civil Engineering, Shenzhen University

Geological Hazards: Data, Mechanisms, Technologies, and Applications

Chong Xu[1,2]

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[2] School of Geology and Mining Engineering, Xinjiang University, Urumqi, China, 830017

Graphical abstract

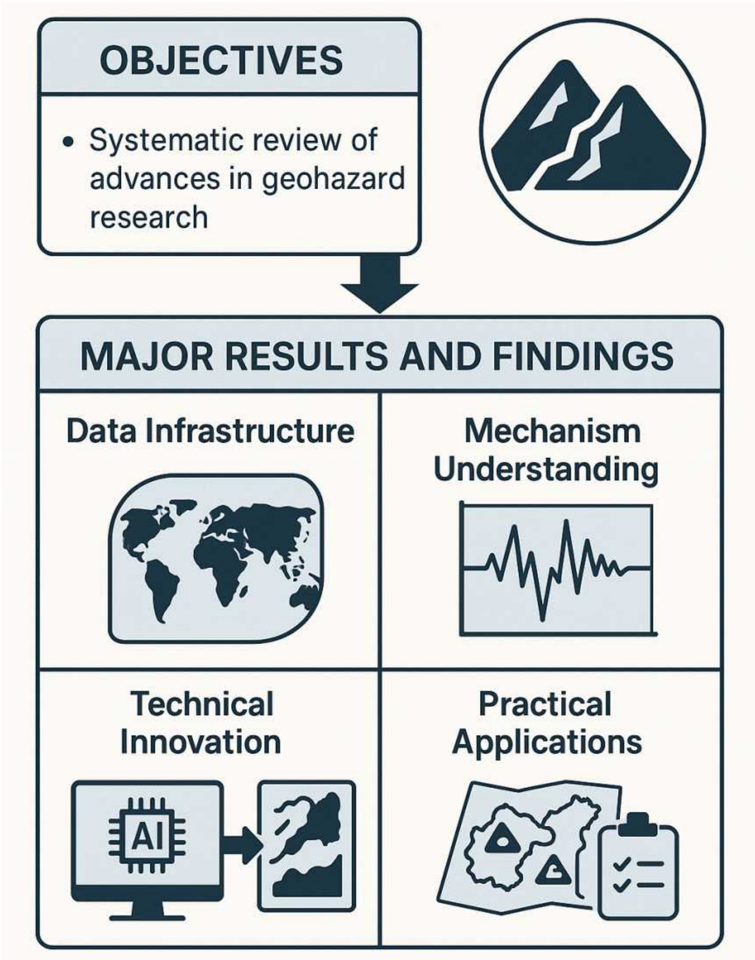

Fig.1 An integrated framework from data to application

1 Objectives and Methodology

This study aims to systematically review recent advances in geohazard research, with a particular focus on data development, mechanism analysis, and technical innovation related to landslide relics, earthquake-triggered landslides, and rainfall-induced landslides. The objective is to build a comprehensive scientific system that integrates multi-source data acquisition, hazard mechanism exploration, and AI-driven risk assessment and early warning technologies.

Methodologically, the research is anchored on large-scale geospatial data construction, including a landslide relics database covering over 10 million km² and comprising approximately 2 million landslide records. Additionally, landslide inventories triggered by hundreds of global earthquakes and rainfall events were compiled, resulting in over 600,000 samples for each trigger type. Advanced remote sensing, event-based landslide extraction methods, and machine learning models—such as Random Forest and XGBoost—were employed to analyze spatial patterns and control factors of mass movement. The study also explored the application of big data analytics and probabilistic modeling to enhance the accuracy and interpretability of landslide risk assessment.

2 Major results and findings

(1) Data Infrastructure: A global landslide relics database was developed, covering more than 10 million km² with around 2 million mapped landslide features. More than 600,000 earthquake-triggered and 600,000 rainfall-induced landslides were systematically collected from historical events, forming the basis for global-scale hazard analysis.

(2) Mechanism Understanding: The study confirmed the strong control of seismogenic fault geometry—especially fault dip and rupture depth—on the spatial distribution of earthquake-triggered landslides. It also revealed that both normal and reverse faulting earthquakes produce similar landslide distribution patterns, providing new insights for source fault identification, fault mechanism interpretation, and seismic intensity zoning.

(3) Technical Innovation: Rapid mapping techniques for coseismic landslides were developed, significantly reducing response time after major earthquakes. By integrating machine learning methods, the study transitioned from traditional relative susceptibility models to absolute probability models. This enabled the generation of the first-generation national earthquake-induced landslide probability map of China, offering improved scientific support for emergency response and disaster preparedness.

(4) Practical Applications: The results have been applied in various operational contexts, including post-earthquake emergency response, seismic intensity revision, infrastructure site selection, and disaster preparedness exercises. These outcomes have contributed directly to improving China's geohazard prevention and risk governance capabilities.

Key Technologies for Digital Intelligence-Empowered Resilience Enhancement of Highways

Ning Xie[1,2]

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Graphical abstract

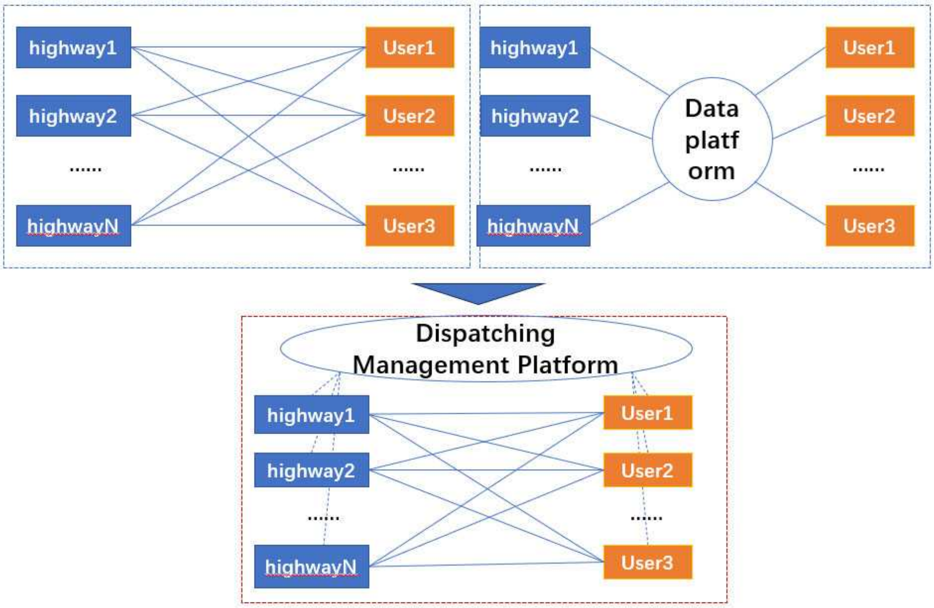

Figure 1 Graphical abstract

1 Objectives and Methodology

Enhancing the safety and resilience of transportation infrastructure is both a critical national strategic priority and a cutting-edge focus in global transportation technology development. In scenarios involving natural or human-induced disasters, insufficient resilience (e.g., robustness and rapid response capability) can severely impact infrastructure integrity and public safety. One of the key challenges lies in the lack of reliable information dissemination channels. Highways should transition from the traditional approach of solely relying on self-built warning systems to a collaborative model with external partners. Leveraging the vast user base of modern transportation networks can enable lightweight, wide-reaching information services and early warnings.

2 Major results and findings

Addressing the three major challenges of collaborative information services—spanning multiple regions, involving diverse industry stakeholders, and engaging full-scale user participation—this study examines a tiered data provisioning framework for highways. Based on data quality maturity and coverage scope, data elements are classified into a three-tier gradient:

- Tier 1 data currently supports nationwide services;
- Tiers 2 and 3 data will progressively accumulate technical expertise through regional pilots.

User data needs are segmented into pre-trip and in-trip phases, with distinct subcategories. Automakers prioritize safety-related, technically mature, and high-quality stable data, while mitigating information redundancy from excessive data inputs. The study explores a cross-domain information service architecture and its evolution for highways, delivered via two pathways: telecom operator platforms and automaker platforms.

Long-term trends indicate that as highway-side operational monitoring capabilities and data quality improve, data scalability will expand and application scenarios will diversify. The user ecosystem will remain multi-stakeholder. Leveraging next-gen digital infrastructure (e.g., trusted data spaces) enhances both the resilience of highway systems and the feasibility, security, and value proposition of data services.

Tornado-induced Risk Analysis of Railway System Considering the Correlation of Parameters

Cheng Yang[1,3], Weihao Yin[2], Yanwen Huang[1,4], and Hanbing Kou[1]

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Graphical abstract

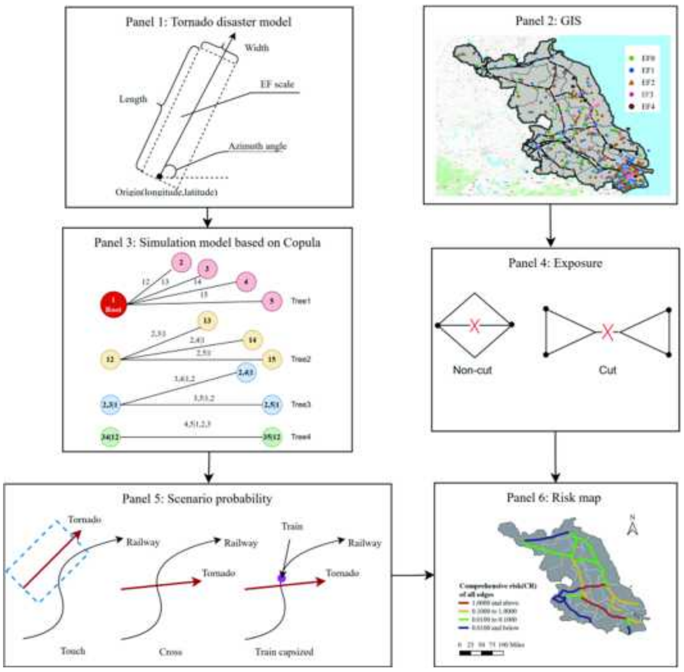

Figure 1 Graphical abstract

1 Objectives and Methodology

This study investigates tornado-induced risks to the high-speed rail (HSR) network in China's Yangtze River Delta region. Despite possessing an extensive and densely constructed HSR system, the region's unique geographical characteristics render it particularly vulnerable to frequent tornado events and other extreme meteorological hazards. Notably, current academic research remains insufficient in addressing tornado risk assessment for railway transportation systems.

To bridge this research gap, we have developed an innovative systematic framework for tornado risk assessment in railway networks. The methodology integrates:

(1) Stochastic Field Modeling: Employing C-vine copula to capture parameter dependencies and construct probabilistic hazard fields.

(2) Scenario Development: Defining three disruption scenarios based on spatial relationships between tornado events and HSR operations: (i) Speed reduction; (ii)

Infrastructure damage; (iii) Tornado-induced derailment.

(3) Comprehensive Risk Assessment: Implementing a user equilibrium assignment model to: (i) Identify delay-prone segments; (ii) Evaluate network capacity degradation; (iii) Conduct sensitivity analysis; (iv) Quantify system-wide resilience metrics.

2 Major results and findings

Table 1 Major results and findings

Major findings	Specific manifestations
Quantitative assessment of risk exposure across different lines	The study presents quantitative analysis results for: Physical risk; Functional risk; Non-cut edge risk; Comprehensive risk
Precise identification of vulnerable segments within the railway network	The results demonstrate that the Anting-Zhenjiang line exhibits significant functional risk characteristics, leading to notable increases in operational travel time. Comprehensive risk assessment reveals that both the Anting-Zhenjiang and Yangzhou-Haian lines display the highest composite risk levels under tornado disaster scenarios.

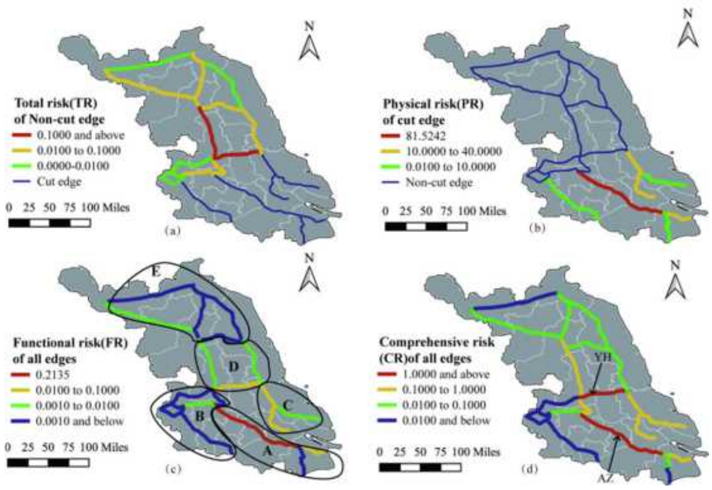

Figure 2 Risk map of (a) TR, (b) PR, (c) FR, (d) CR.

基于大型土工离心机试验的极端降雨诱发在役公路路基滑坡灾害机理研究

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随着全球气候变化，极端天气事件频发，随之伴生的边坡失稳问题日益突出。2024 年梅大滑坡事件为典型例证，灾害导致 48 人死亡 30 人受伤。其对交通基础设施安全构成了严重威胁，并导致了重大的人员伤亡和恶劣的社会影响。为了深入理解此类灾害的发生机制，本研究利用大型土工离心机试验，模拟并分析了降雨条件下路基边坡失稳及流动行为，旨在为防灾减灾提供科学依据和技术支持。

本次研究中，首先对现场地形地貌、地层岩性、滑坡特征以及气象数据进行了详尽的调查分析。并根据滑坡的关键特征构建了相似比为 1:100 的梅大滑坡模型，并采用原位土作为试验边坡介质，以确保实验样本的物理力学性质与原型相似。通过离心机来修正试验的尺寸效应，采用坡体内部渗水的方式模拟地下水的运移以及对边坡土体的作用过程。更为关键的是，利用溶蚀盐颗粒的方法，较好的还原了原状土体长期受降水内侵蚀导致的松散结构。试验期间，采用了多种监测技术，如高速摄影系统、激光位移计、孔隙水压力等，以实时记录边坡表面和内部演变特征。

试验结果表明，受到不透水层和挡土墙的影响，不同深度处的土体表现出差异化的响应模式，坡脚处土体孔隙水压上升较快且存续时间较长，并且边坡土体黏土矿物含量高，吸水软化作用显著，因而边坡下部最先失稳。进而诱发边坡上部崩塌溃散，边坡整体呈现牵引式流滑特征，与现场滑坡特征高度一致。此外，试验还揭示了边坡失稳后的流动路径具有明显的分异性，这取决于原始地形地貌以及土体结构特性。同时，对照试验组发现，再不还原原状土体结构的情况下，边坡仅发生沉降变形，而不会发生溃散失稳，证明了原状土体内侵蚀形成脆弱力链结构可能是重要的孕灾因子。

通过对梅大滑坡案例的深入剖析，本研究不仅明确了梅大高速公路边坡失稳流滑机制，也明确了东南区域因降雨和地下水导致的公路路基边坡土体性质劣化的根本机理。进而，针对类似地质条件下，根据地层信息、微地貌特征、降雨监测数据等建立数学模型，提出评估方法与预警指标体系，最终基于韧性理论有针对性地提出设计与加固方案，综合提升我国道路路基边坡防灾韧性。

Ecology and Resilience of Transportation Infrastructure: Theory and Practice

Hui Li[1]

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Graphical abstract

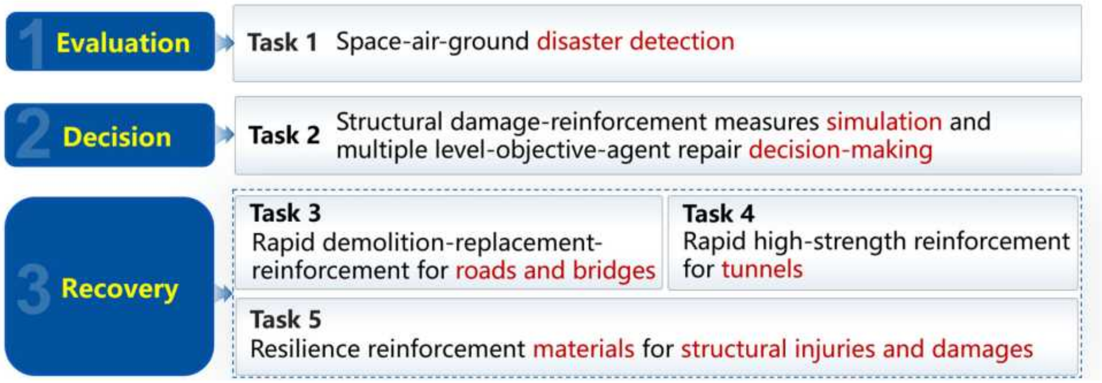

Figure 1 Framework and Methodology of Emergency Repair and Rapid Recovery for Transportation Infrastructure After Disasters

1 Objectives and Methodology

This project adopts a safety-efficiency-economy oriented approach, targeting two major regions, two types of facilities, three structural categories, and nine disaster scenarios. Focusing on full-chain technological innovation across "disaster assessment → emergency repair decision-making → rapid traffic restoration", it conducts research in five key areas:

(1) Three-dimensional detection and assessment ;
(2) Emergency repair decision-making for critical transport corridors ;
(3) Rapid traffic restoration for roads and bridges ;
(4) Targeted tunnel reinforcement ;
(5) Resilient rehabilitation of damaged components.

2 Major results and findings

The scientific research for Task 2 led by Tongji University, leveraging a three-tier R&D demonstration system of laboratory development → full-scale pilot testing → engineering validation, has delivered comprehensive integrated innovations:

(1) Establishing a multi-scale, multi-process simulation platform to reconstruct disaster scenarios;
(2) Revealing structural failure mechanisms and rapid reinforcement principles for all structural types under multiple disasters;
(3) Developing a multi-objective optimization model balancing efficiency-safety-economy;
(4) Creating a dynamic decision-making system featuring multi-tiered, multi-objective, multi-agent coordination.

This provides theoretical underpinnings for post-disaster rapid emergency repair operations.

Design theory and method of high performance cement-based materials for improving traffic facility resilience

Cong Ma [1]

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msk2017@188.com

Graphical abstract

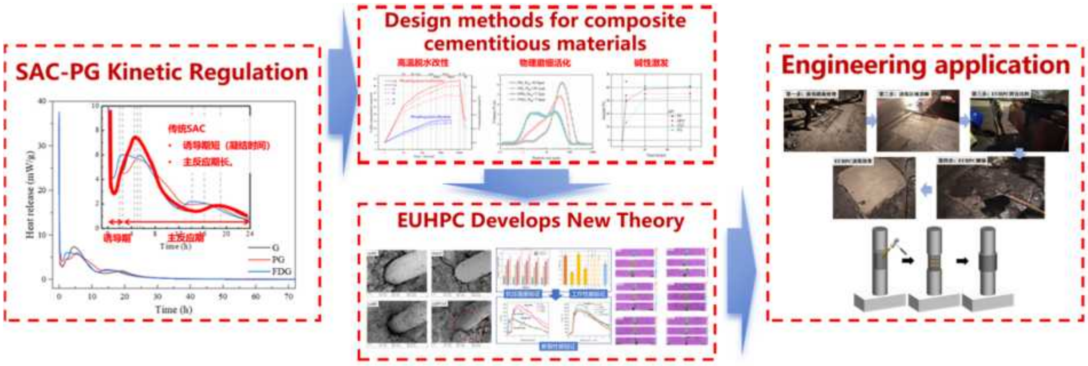

Figure 1 Graphical abstract

1 Objectives and Methodology

This research delivers a new generation of ultra-early-strength engineered UHPC designed for the rapid repair of transport concrete suffering from coastal deterioration. By integrating slag and thermally activated waste gypsum into a ternary SAC system, the matrix accelerates early hydration, sustains long-term strength, and markedly improves resistance to chloride ingress.

Workability is maintained through a tailored PCE-borax admixture, while silica fume and nano-calcium carbonate refine the interfacial transition zone. A hybrid blend of steel, PVA and basalt fibres enhances fracture toughness. Field trials on coastal highways and seaport piers have validated the material's ability to open traffic within hours and to extend service life significantly, offering a unified solution for early strength, stability and durability.

2 Major results and findings

Table 1 Major research results

	Major research results
1	The efficient utilization of phosphogypsum in SAC system was realized for the first time, and the super early strength performance was maintained when the dosage reached 25%.
2	Sulphoaluminate cement exhibits a pronounced sensitivity to acidic and alkaline conditions. The duration of the induction phase of the cement can be regulated through modulation of the gypsum's acidity and alkalinity, thus facilitating control over the setting time.
3	The rate at which gypsum dissolves establishes the concentration of ions,

	thereby governing the reaction rate of the primary hydration phase of cement. Altering the properties of gypsum to modulate the initial behavior of sulphoaluminate cement represents an efficacious approach.

Table 2 Major research findings

	Major research findings
1	The theory of "fiber scale coordination" for SAC-based UHPC is proposed to achieve the simultaneous improvement of toughness and strength through steel-organic-inorganic fiber hybridization.
2	The integrated design method of "early strength-stability-durability" for SAC-based UHPC is established to provide a technical paradigm for rapid repair of traffic facilities

Principles and Methods for Geological Disaster Emergency Rescue

Yonggang CHENG [1]

[1] Sichuan Urban and Rural Development Design Company, Chengdu, 610000 China, 657514364@qq.com

1 Objectives and Methodology

This study aims to systematically establish emergency response concepts and methodologies for engineering slope hazards, focusing on hazard identification, mechanism analysis, and emergency treatment techniques. The objective is to build a comprehensive technical framework that integrates rapid site investigation, hazard mechanism exploration, and effective emergency treatment measures for engineering slope disasters.

Methodologically, the research is anchored on extensive engineering practice cases and field investigations of slope hazard emergencies. The study employs qualitative analysis methods including engineering geological comparison, deformation characteristic analysis, and existing structure damage assessment. Advanced site investigation techniques, engineering geological classification methods, and failure mode analysis were utilized to establish emergency response principles and treatment methods. The research also incorporates dynamic monitoring approaches and real-time feedback mechanisms to enhance the effectiveness and reliability of emergency response measures.

2 Major results and findings

(1) Emergency Definition and Characteristics: Established a clear definition of engineering slope hazard emergencies as sudden disasters that exceed engineering tolerance or control capacity, threatening protected structures within short timeframes, requiring emergency measures to achieve slope stability factors above 1.05. Six key characteristics were identified: diverse triggering factors, sudden occurrence, exceeding engineering capacity, short-term threats, specific stability requirements, and emergency nature.

(2) Emergency Response Principles: Developed fifteen fundamental principles for emergency response, including accurate hazard investigation, rapid response, precise targeting, appropriate conservatism, active drainage, secondary disaster prevention, permanent-temporary integration, local material utilization, convenient construction, thorough investigation, avoiding hasty conclusions, safety assurance, appropriate treatment intensity, dynamic monitoring, and environmental protection.

(3) Analysis Methodology: Established a systematic analysis framework following the principle of "qualitative analysis as foundation, quantitative analysis as means," emphasizing field investigation-centered qualitative methods including engineering geological comparison, deformation sign analysis, and existing structure damage assessment for rapid emergency decision-making.

(4) Treatment Technologies: Developed diversified emergency treatment methods including unloading and counter-pressure techniques, surface and groundwater interception and drainage, lightweight passive support systems, prestressed active reinforcement, and riverbank erosion control measures, validated through multiple

successful engineering cases demonstrating effectiveness in emergency slope stabilization.

Paralel Session B1 Summary:

1 Basic Information

Chair: Xianfeng LIU Professor, Southwest Jiaotong University

Co-chair: Hui LI Distinguished Professor, Chang Jiang Scholar, Tongji University

Time: 13:30-17:30, July 21, 2025

Location: Room 310, Beijing International Convention Center

2 Introduction

China's highway and railway network has achieved remarkable scale, with total mileage exceeding 5.5 million kilometers, ranking first globally and representing a critical component of the nation's infrastructure backbone. This extensive transportation network spans diverse topographic and geomorphological units, traversing mountainous regions, plains, deserts, and coastal areas, while operating within complex disaster-prone environments characterized by varied geological conditions and climatic zones. The network faces persistent threats from frequent natural disasters, including mountain floods, debris flows, landslides, earthquakes, and extreme weather events that occur regularly along transportation corridors. Different road segments exhibit distinctly varying disaster development backgrounds, spatial distribution patterns, temporal activity characteristics, and destructive capacities, resulting in complex and multifaceted disaster mechanisms that significantly complicate risk assessment and hazard prediction. These complexities create substantial challenges for effective disaster detection, monitoring, and early warning systems. Furthermore, the current lack of systematic and integrated post-disaster emergency repair decision-making frameworks, coupled with insufficient repair efficiency and limited technological capabilities, severely impede emergency rescue operations and disaster response efforts. This situation poses serious and escalating threats to public safety, economic stability, and overall transportation security, potentially disrupting critical supply chains and emergency services. Consequently, there is an urgent and pressing need to develop comprehensive emergency repair and rapid restoration technologies specifically designed for long-distance linear transportation infrastructure, incorporating advanced materials, intelligent monitoring systems, and automated repair mechanisms to substantially enhance China's post-disaster emergency repair and restoration capabilities for transportation infrastructure while ensuring resilient and sustainable network operations.

2 Discussion

2.1 Geological Hazards: Data, Mechanisms, Technologies, and Applications

Director Xu Chong's research team at the National Institute of Natural Hazards, Ministry of Emergency Management, systematically reviewed recent advances in geohazard research, focusing on data development, mechanism analysis, and technical innovation related to landslide relics, earthquake-triggered landslides, and rainfall-induced landslides to establish a comprehensive scientific framework integrating multi-source data acquisition, hazard mechanism exploration, and AI-driven risk assessment and early warning technologies. The research is anchored on large-scale geospatial data construction, developing a global landslide relics database covering over 10 million km^2 with approximately 2 million records, alongside inventories of more than 600,000 earthquake-triggered and 600,000 rainfall-induced landslides, analyzed using advanced remote sensing technologies, machine learning models (Random Forest, XGBoost), and big data analytics to examine spatial patterns and controlling factors. Major achievements include: establishing global-scale landslide data infrastructure; revealing the strong control of seismogenic fault geometry on earthquake-triggered landslide spatial distribution, providing new insights for fault mechanism interpretation and seismic intensity zoning; developing rapid coseismic landslide mapping techniques and achieving the transition from traditional relative susceptibility models to absolute probability models, generating China's first national earthquake-induced landslide probability map; and successfully applying research outcomes in post-earthquake emergency response, seismic intensity revision, infrastructure site selection, and disaster preparedness exercises, directly enhancing China's geohazard prevention and risk governance capabilities.

2.2 Key Technologies for Digital Intelligence-Empowered Resilience Enhancement of Highways

Ning Xie’s team systematically synthesized advances in "digital-intelligence-enabled resilience enhancement for highways," focusing on collaborative information services across multi-regional, cross-industry, and full-user scenarios. They devised a three-tier data-provisioning framework graded by data-quality maturity and coverage: Tier 1 already underpins nationwide services, while Tiers 2 and 3 accumulate technical know-how through regional pilots. User data needs are segmented into pre-trip and in-trip phases, with automakers prioritizing safety-critical, mature, high-quality, and stable data while suppressing redundancy. The study proposes a cross-domain information-service architecture delivered via two pathways—telecom-operator platforms and automaker platforms—and charts its evolutionary trajectory. Long-term trends indicate that as roadside monitoring capabilities and data quality improve, data scalability will expand and application scenarios diversify within a persistently multi-stakeholder ecosystem. Leveraging next-generation digital infrastructures such as trusted data spaces simultaneously strengthens highway-system resilience and enhances the feasibility, security, and value proposition of data services.

2.3 Tornado-induced Risk Analysis of Railway System Considering the Correlation of Parameters

Cheng Yang's team systematically synthesized advances in "tornado-induced risk analysis of railway systems accounting for parameter correlations," focusing on the high-speed rail (HSR) network in China's Yangtze River Delta—a region highly exposed to frequent tornadoes yet largely overlooked in academic research. They developed an innovative framework that integrates (1) stochastic-field modeling via C-vine copulas to capture parameter dependencies and construct probabilistic hazard fields; (2) three operational-disruption scenarios—speed reduction, infrastructure damage, and tornado-induced derailment; and (3) comprehensive risk assessment using a user-equilibrium assignment model to pinpoint delay-prone segments, quantify network-capacity degradation, and derive system-wide resilience metrics. The study produced the first quantitative risk maps for physical, functional, non-cut-edge, and composite risks across the network, identifying the Anting–Zhenjiang and Yangzhou–

Haian lines as the most vulnerable. Published in Reliability Engineering & System Safety and other journals, the outcomes directly support HSR emergency dispatching, resilience enhancement, and operational decision-making.

2.4 Research on the Mechanism of Landslide Disasters on In-service Highway Embankments Induced by Extreme Rainfall Based on Large-scale Geotechnical Centrifuge Tests

Prof. Chongqiang Zhu's team systematically investigated the failure mechanisms of in-service highway embankment slopes triggered by extreme rainfall through large-scale geotechnical centrifuge testing. Anchored on the 2024 Meida landslide—48 fatalities, 30 injuries—the study reconstructed a 1:100 scale model using undisturbed site soils and dissolved-salt particle erosion to replicate long-term internal weathering. Centrifuge-enhanced simulations reproduced groundwater infiltration and differential pore-pressure responses beneath impermeable layers and retaining walls, revealing basal failure induced by rapid pore-pressure rise and clay softening, followed by retrogressive flow-sliding that mirrored field observations. Control tests confirmed that loss of the in-situ weathered fabric only caused settlement, not collapse, identifying the weakened internal fabric as a critical preconditioning factor. The findings elucidate the deterioration mechanisms of highway embankments in southeast China under coupled rainfall–groundwater actions, and provide a quantitative framework integrating stratigraphic, micro-topographic, and rainfall data for risk assessment, early-warning indicators, and resilience-based design and retrofitting strategies.

2.5 Key Technologies for Emergency Repair and Rapid Restoration of Infrastructure

Prof. Hui Li's team systematically advanced the ecology and resilience of transportation infrastructure through a safety-efficiency-economy paradigm, targeting two regions, two facility types, three structural categories, and nine disaster scenarios. Leveraging a three-tier R&D chain—laboratory development → full-scale pilot testing → engineering validation—they created a multi-scale, multi-process simulation platform to reconstruct disaster events, elucidated failure mechanisms and rapid-strengthening principles under multi-hazard loading, and developed a multi-objective optimization model balancing safety, efficiency, and cost. A dynamic decision-making framework featuring multi-tier, multi-objective, multi-agent coordination was established to guide the full-cycle workflow of post-disaster assessment, emergency repair, and rapid traffic restoration for roads, bridges, and tunnels. The integrated innovations provide theoretical foundations and practical tools for resilient rehabilitation of damaged transport assets.

2.6 Design Methods for Key Materials Improving Resilience of Transportation Infrastructure

Cong Ma's team systematically advanced the design theory and high-performance formulation of ultra-early-strength engineered UHPC tailored for rapid, one-stop repair of coastal traffic infrastructure. By integrating slag and thermally activated phosphogypsum into a ternary sulphoaluminate cement (SAC) matrix, they achieved—at 25 % gypsum dosage—the first demonstration of super-early strength without compromise, while regulating induction-period kinetics through controlled gypsum acidity/alkalinity. Silica fume, nano-calcium carbonate and a PCE-borax superplasticizer refined the interfacial transition zone for workability, and a steel-PVA-basalt hybrid fibre system realized a "fibre-scale-coordination" mechanism that simultaneously boosts toughness and strength. Field deployments on coastal highways and seaport piers validated traffic reopening within hours and substantial service-life extension, establishing an "early-strength–stability–durability" integrated design paradigm for resilient, rapid repair of transport facilities.

2.7 Principles and Methods for Geological Disaster Emergency Rescue

Dr. Cheng Yonggang established a comprehensive emergency response framework for engineering slope hazards, integrating rapid site investigation, mechanism analysis, and treatment techniques based on extensive field practice and qualitative analysis methods including engineering geological comparison and deformation assessment. Key achievements include: defining slope emergencies as sudden disasters exceeding engineering capacity and threatening structures within short timeframes, requiring stability factors above 1.05; developing fifteen fundamental response principles covering rapid investigation, precise targeting, active drainage, and dynamic monitoring; establishing a "qualitative-foundation, quantitative-means" analysis framework emphasizing field-centered methods; and creating diversified treatment technologies including unloading techniques, water interception systems, lightweight support, and prestressed reinforcement, validated through successful engineering cases to provide systematic guidance for slope hazard emergency response.

Paralel Session B2

Topic: Artificial Intelligence for Smart Construction and Maintenance

Chair: Danhui Dan, Professor, Tongji University
Cochair: Liangfu Ge, Research Assistant Professor, The Hong Kong Polytechnic University;
Qianqing Wang, PostdoctoralFellow, Ecole polytechnique fédérale de Lausanne (EPFL);
Xuewen Yu, Postdoctoral Fellow, Nanyang Technological University

Introduction:

Artificial Intelligence (AI) is redefining the way we design, build, and maintain civil infrastructure. By integrating technologies such as digital twins, intelligent sensing, robotics, and edge-cloud computing, AI is enabling more resilient, efficient, and sustainable infrastructure systems. This session brings together researchers, engineers, and practitioners to explore the latest AI-driven innovations across the infrastructure lifecycle—from construction and monitoring to predictive maintenance and structural optimization. We invite contributions that highlight both fundamental research and practical applications of AI in civil engineering and smart infrastructure. Topics of interest include, but are not limited to:

1. Digital Twins and BIM for Infrastructure Planning: Leveraging Building Information Modeling (BIM) and digital twin technologies for real-time simulation, predictive maintenance, and lifecycle management of bridges and other structures.
2. Intelligent Sensing Systems and Automated Maintenance Workflows: AI-powered sensor networks and robotic platforms for autonomous inspection and continuous monitoring, minimizing downtime and human risk.
3. Edge-Cloud Architectures for Real-Time Structural Health Monitoring: Distributed computing frameworks that fuse edge devices with cloud platforms to enable scalable, real-time health monitoring and decision-making.
4. Robotics and Autonomous Systems for Construction: Emerging applications of UAVs, UGVs, and robotic swarms for on-site construction and automated fabrication.
5. Generative Design and AI-Assisted Structural Optimization: Advances in structural design methods through AI-driven generative models and optimization strategies.

Speech:

Exploration Application of AI Technology in the Analysis of Bridge Structure Health Monitoring Data
Yufeng Zhang, Lianfa Wang, Yichao Xu, Xinhe Zhang, Jiawei Xu, Yifan Fu, JSTI group

AI-Empowered Intelligent Bridge Construction and Maintenance: R&D and Practice of the "Qiaotoubao" Platform
ZHONG Jiwei, State Key Laboratory of Bridge Intelligent and Green Construction

Development of Noncontact Sensing Technologies for Construction Quality Inspection of Bridges

Yongding Tian, Yangfeng Lyu, and Xicheng Yang, School of Civil Engineering, Southwest Jiaotong University,

Smart Ground Robotic System for Automated Structural Inspection and Mapping

Liangfu Ge, The Hong Kong Polytechnic University

Construction of Bridge Cluster Monitoring and Governance Platform with Cross-Platform Multi-Tier Networking Technology

Xin Yan, Han Wei, and Xiaojing Wang, Highway Research Institute of the Ministry of Transport,

Exploration Application of AI Technology in the Analysis of Bridge Structure Health Monitoring Data

Yufeng Zhang[123], Lianfa Wang[123], Yichao Xu[123], Xinhe Zhang[13], Jiawei Xu[13], Yifan Fu[12]
[1] JSTI group, Nanjin, 210012, Jiangsu, China, zyf174@jsti.com
[2] State Key Laboratory of Safety, Durability and Healthy Operation of Long Span Bridges
[3] Observation and Research Base of Transport Industry of Structural Safety and Long-term Performance of Long-span Cable Supported Bridges

Graphical abstract

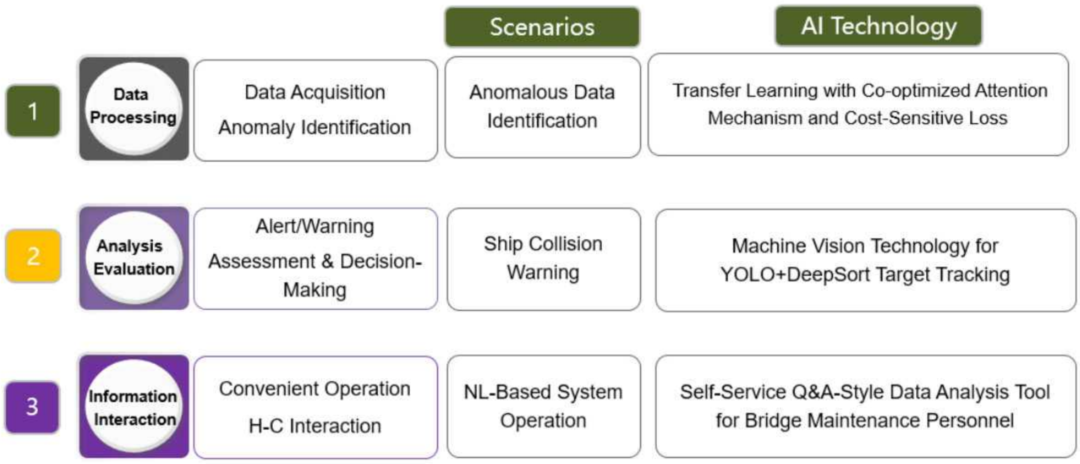

Figure 1 Three Key Directions of AI Technology Application in SHM Data Analysis

1 Objectives and Methodology

Structural health monitoring (SHM) technology has become a vital means of assessing bridge conditions and ensuring structural safety & integrity, with rapid advancements in recent years. Effectively utilizing the massive volumes of multi-source, heterogeneous, and strongly coupled data acquired through SHM represents a core challenge requiring resolution. The continuous evolution of AI technology—from "rule-based reasoning" to the "deep learning" stage—has seen explosive growth, while the emergence of large language models (LLMs) has accelerated the application of AI in SHM data analysis. This report addresses the primary bottlenecks and challenges in data analysis including demand context, data processing, analysis & evaluation, and information interaction. Besides, case studies are presented on the research and application of: 1) Transfer learning with co-optimized attention mechanisms and cost-sensitive loss for bridge anomaly data identification; 2) YOLO+DeepSORT target tracking technology in machine vision-based ship collision warning systems; 3) LLMs for Q&A-style data analysis. The core advantages of AI technology in monitoring data analysis lie in processing high-dimensional nonlinear data, enabling automated decision-making, and facilitating rapid data retrieval. Future advancements are projected to evolve toward multimodal fusion (acoustic+visual+sensor), model generalization (cross-bridge-type transfer), lightweight AI models (adaptable for edge deployment), and unsupervised learning.

2 Major results and findings

Case studies are presented on exploratory AI applications for data processing, analysis & evaluation, and information interaction of SHM data.

(1) Multiple AI technolodgy have been implemented in monitoring data analysis, providing novel approaches for efficient data cleansing, performance assessment, and convenient operations.

(2) For SHM anomaly identification, we transformed raw time-series data into image representations to detect abnormalities in temporal curves using deep learning networks. To address critical challenges of data imbalance adversely affecting anomaly detection and cross-domain data characteristics hindering model generalization, we implemented CBAM attention mechanisms enabling dynamic selection of salient input features. Leveraging misclassified samples from validation set confusion matrices, we constructed a cost matrix assigning differential weights to classification errors across data types—enhancing training efficiency and increasing recognition accuracy.

(3) For machine vision-based ship collision warning systems, our enhanced YOLO architecture reduced wave interference, achieving precise vessel and buoy recognition. We pioneered multi-scale, multi-target tracking technology and established a multi-vessel database. Distant objects were detected through shallow-deep feature fusion, with false positives eliminated via multi-frame comparison. Ship positions were determined through multi-layer detection against vessel templates, enabling accurate long-range identification.

(4) In NL-based system operations, we developed a self-service Q&A-style data analysis tool for bridge maintenance personnel. This implements natural language processing for monitoring data queries and visualization.

AI-Empowered Intelligent Bridge Construction and Maintenance: R&D and Practice of the "Qiaotoubao" Platform

ZHONG Jiwei[1,2]
[1]State Key Laboratory of Bridge Intelligent and Green Construction, Wuhan, Hubei, China,
[2]China Railway Major Bridge Engineering Group Co., Ltd., Wuhan, Hubei, China.

Graphical abstract

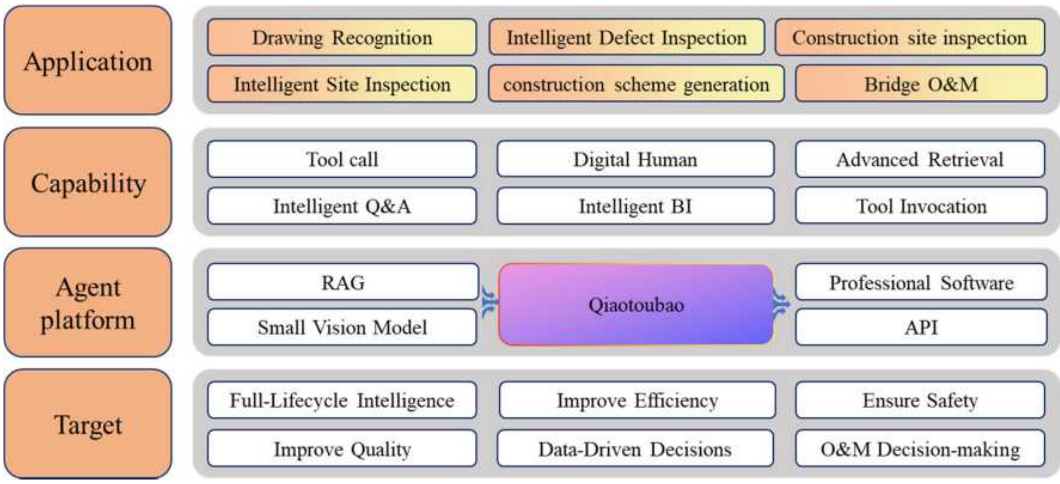

Figure 1 Graphical abstract

1 Objectives and Methodology

This research aims to address the unique challenges of deeply integrating Artificial Intelligence (AI) technology with the full lifecycle of bridge construction and maintenance. Traditional bridge engineering is characterized by non-standardized data, knowledge intensity, and complex scenarios, leading to core difficulties for AI applications such as small-sample/zero-sample learning, multi-modal information fusion, large model "hallucinations," and data security/privacy. To systematically address these issues, we have developed the "Qiaotoubao" intelligence platform.

The core methodology of this research is a pragmatic and efficient hybrid technical path. The platform's overall architecture adopts a layered design, with its technical implementation path as follows:

Core Technology Selection: The primary technical route combines Retrieval-Augmented Generation (RAG) with Prompt Engineering, efficiently utilizing existing domain knowledge bases (e.g., standards, drawings, reports) to ensure the accuracy and timeliness of generated content and effectively mitigate the "hallucination" problem. Meanwhile, Fine-tuning is used as an auxiliary method for highly specialized core tasks (e.g., precise quantitative identification of specific defects) to enhance the model's professional capabilities in specific scenarios.

Multi-modal Capabilities: The platform deeply integrates Large Language Models (LLM) and Visual Large Models (VLM). It can process not only textual standards and reports but also understand multi-modal information such as drawings, UAV inspection videos, and on-site monitoring images, enabling an "event-level" understanding of complex work conditions.

Knowledge Engine: A Knowledge Graph for the bridge engineering domain has been constructed, transforming discrete, unstructured data (such as over 200 inspection reports) into structured knowledge, providing high-quality support for RAG and intelligent decision-making.

Deployment Model: A "cloud + on-premise" hybrid deployment model is adopted. General-purpose large models are deployed in the cloud for powerful computing, while specialized models and applications involving core data are deployed locally. This model ensures high performance while meeting the security and confidentiality requirements of project data.

Through this platform, we aim to transform AI technology into a series of practical and quantifiable applications, empowering the intelligent upgrade of bridge design, construction, and maintenance.

2 Major results and findings

The "Qiaotoubao" platform has been validated in multiple practical application scenarios and has achieved significant results. The following are the quantitative outcomes of some core application cases:

Table 1. Summary of Core Application Case Results for the "Qiaotoubao" Platform

Application Stage	Application Case	Pain Points of Traditional Methods
Design	Intelligent Drawing Recognition & Modeling	Manual drawing interpretation is time-consuming and prone to errors.
Construction	Intelligent Site Inspection	Manual inspection is inefficient with limited coverage, making it difficult to detect violations and hazards in real-time.
operation and maintenance	UAV-based Intelligent Defect Inspection	Manual inspection is time-consuming, costly, and involves high risks for high-altitude work.
operation and maintenance	Intelligent O&M Decision Decision Support	Decisions rely on expert experience and lack data support; writing inspection reports, especially the conclusions and recommendations section, is laborious.

Development of Noncontact Sensing Technologies for Construction Quality Inspection of Bridges

Yongding Tian [1*], Yangfeng Lyu [1], and Xicheng Yang [1]
[1] School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031 China, civil_tyd@swjtu.edu.cn

Graphical abstract

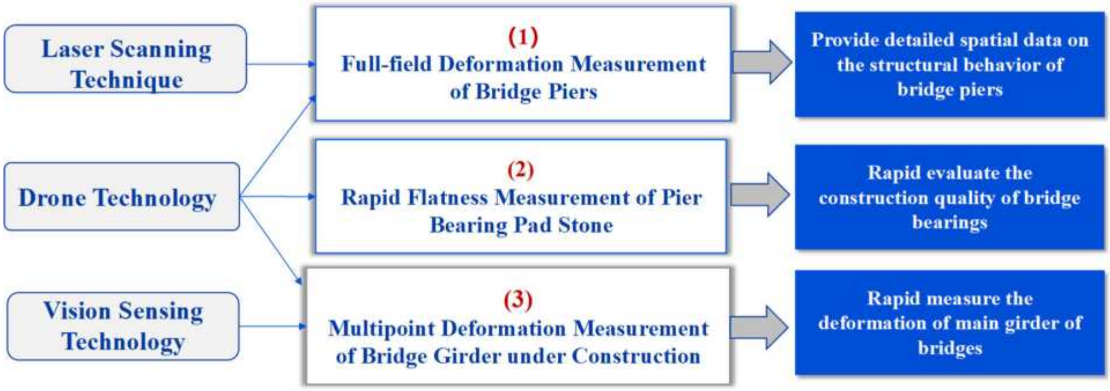

Figure 1 Graphical abstract

1 Objectives and Methodology

To address the strategic necessity of intelligent construction for major national infrastructure, and to tackle prominent issues in the quality and rapid detection and evaluation of bridge construction, noncontact sensing techniques for the rapid construction quality inspection of bridge pier, bearing pad and main girder have been proposed using the advanced sensing technology and deep learning. Firstly, a high-precision calculation method for the excessive deformation of pier steel plates using three-dimensional laser scanning and deep learning will be introduced. Secondly, a rapid measurement method and equipment based on a multi-rotor drone platform will be described for assessing the flatness of the bridge bearing pad, and a vision guided path planning and navigation algorithm. Finally, a noncontact vision-based method will be presented for bridge deformation measurement under object occlusion, which is capable of operating in complex environments such as those with object occlusion and varying lighting conditions.

2 Major results and findings

(1) Construction quality inspection of a steel-concrete composite bridge pier

Steel-concrete bridges have been widely constructed within road networks due to their distinctive mechanical properties. Nevertheless, issues related to construction quality, such as concrete pouring blockages, steel plate delamination, and steel plate de-formation, frequently occur, posing significant risks to the safe operation of these bridges. This study developed a highly accurate and automated full-field deformation measurement method for the construction quality inspection of steel-concrete composite bridge piers using laser scanning technology and deep learning. The innovative contributions of this study are twofold: (1) a geometric feature-based point cloud simplification algorithm was developed to automatically select sampling points while preserving crucial structural information and reducing the data volume by employing the Fast Point Feature Histogram (FPFH) feature and an improved voxel down-sampling technique; (2) a highly accurate point cloud registration method was devised, in which geometric structure embedding and an attention mechanism were utilized to extract point cloud features, and maximal clique constraints were applied to estimate the positional attitude between two point cloud datasets for full-field deformation extraction and construction quality inspection.

(2) Rapid bearing flatness measurement of bridges with developed drone system

Bearing flatness plays a critical role in ensuring safety during bridge construction and operational maintenance. Conventional approaches for bearing flatness measurement present limitations in terms of economic cost, operational safety risk, and measurement efficiency, particularly when applied to elevated piers in mountainous terrain. To overcome these challenges, this study proposes an innovative quadcopter-based measurement system that integrates an optical prism target and deep learning algorithms. The contribution of this paper includes two aspects: (1) an optimized YOLO-MiniFaster model has been developed through the strategic integration of RepNCSPGELAN modules, a Slim-FPN feature fusion architecture, and a SimAM attention mechanism into the baseline YOLO network, for real-time detection of bridge bearing; (2) a hardware prototype, consisting of a quadcopter aerial platform, optical target module, image acquisition unit, and a flight control module, is designed for the rapid measurement of the bearing flatness.

(3) Deformation measurement of bridge girder under construction

During the construction phase, it is crucial to measure the deformation of large-span prestressed concrete bridges at the cantilever end to ensure construction safety. This study proposes a noncontact vision-based deformation monitoring method for large-span rigid concrete bridges under object occlusion. The proposed approach first integrates the deep learning-based background segmentation network U2-net with an incremental image repair network to detect and repair the occluded images automatically; subsequently, an enhanced target detection algorithm that incorporates the CBAM attention mechanism into the YOLOv8 neural network is used to simultaneously extract displacement data from multiple targets attached to the bridge; The robustness and efficacy of the proposed method are verified through long-term field tests of a large-span rigid concrete bridge under construction.

Published papers

[1] **Yongding Tian**, Yuanyuan Huang, Junhao Zhang, Junhu Shao, Yulin Zhan. Noncontact vision-based deformation measurement of a large-span prestressed concrete rigid-frame bridge under object occlusion[J]. Mechanical Systems and Signal Processing,2025,232: 112774

[2]Yangfeng Lyu, Jiahui Tong, Junhao Zhang, Zhixiang Yu , **Yongding Tian***. Highly Accurate and Automated Point Cloud Regis-tration for Full-field Deformation Measurement and Construction Quality Inspection of a Steel-Concrete Composite Bridge Pier [J]. IEEE Transactions on Instrumentation and Measurement. 2025,Accepted.

Smart Ground Robotic System for Automated Structural Inspection and Mapping

Liangfu Ge [1] and Ayan Sadhu [2]

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Graphical abstract

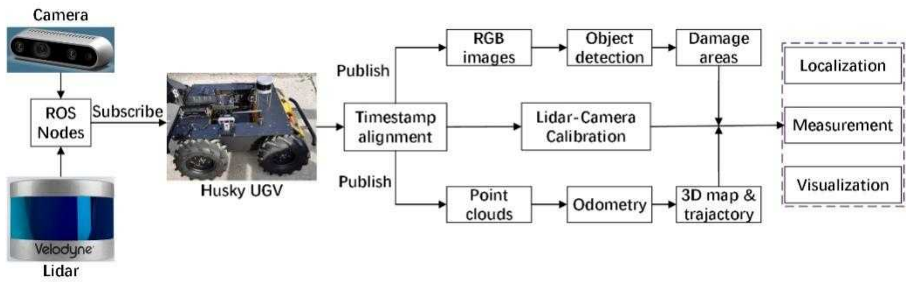

Figure 1. Overall framework of the inspection platform.

1 Objectives and Methodology

Automated visual inspection plays a crucial role in the operational maintenance and safety management of engineering structures, especially in challenging scenarios characterized by difficult access, high repetition, and significant risks. For robotic inspection, Simultaneous Localization and Mapping (SLAM) forms the fundamental basis for detecting, positioning, and quantifying structural defects. However, existing studies on robotic structural inspection often employ SLAM algorithms that require the fusion of information from multiple sensors, leading to complex hardware and parameter configurations. To facilitate the implementation of robotic systems across diverse structures, this study introduces a straightforward yet efficient unmanned structural inspection platform.

The proposed automated inspection system comprises three key modules: a RGB image acquisition module, a LiDAR module, and a robot control module. From the hardware side, these modules are integrated into the Husky UGV (produced by ClearPath) via USB and Ethernet connections. Specifically, RGB images are captured using the stereo camera Intel RealSense D435, offering a resolution of 640×480. The LiDAR module employs a 16-beam Velodyne lidar sensor with a sampling rate of 580,000 points per second. The UGV is controlled by the Linux system with an onboard computer. On the software side, the Noetic ROS is used for sub-scribing, synchronizing, publishing, and processing image and point cloud data for information fusion.

Figure 1 illustrates the overall workflow of the proposed automated inspection platform, which can be divided into the following four steps at each calculation loop.

Step 1: The camera and LiDAR data are published to specific topics and nodes via ROS drivers, allowing frame-by-frame reading of images and point cloud scans by subscribing topics. Then, the wheel motion of the UGV is controlled by a remote controller or the messages from velocity-related topics.

Step 2: The image and point cloud cluster published at each loop are associated with timestamps that can facilitate data alignment. In addition, the calibration across LiDAR and camera is done at the first loop to determine the transformation relationship between the camera and LiDAR coordinate system, which is for quantifying and visualizing the damages.

Step 3: A deep learning based object detection algorithm is used to identify areas of damage, i.e. cracks and spalling on the concrete surfaces. Simultaneously, the point cloud data, processed through an efficient odometry algorithm, generates a 3D map of the inspected structure and the real-time trajectory of the UGV.

Step 4: By aligning timestamps and establishing a transformation mapping between the images and the 3D map, the location of damage and the physical dimensions of the damaged areas can be calculated and can be visualized in the trajectory of the UGV.

Compared to previous UGV-based automated detection platforms, the advantage of the proposed platform lies in its real-time computing capabilities, which are attributed to the implementation of advanced target detection and odometry algorithms. The following subsections will detail the algorithms.

2 Major results and findings

This study introduces a novel Unmanned Ground Vehicle (UGV)-based automated structural inspection platform, equipped with advanced cameras and LiDAR sensors. Two new algorithms are proposed: one for detecting structural damage in images and the other for odometry estimation and 3D mapping based on point cloud data. The proposed improved YOLOv7 algorithm was validated high accuracy on damage detection in a concrete bridge, while the adapted KISS-ICP algorithm demonstrated high precision and efficiency in 3D mapping and locating the UGV. Additionally, the proposed robotic platform achieved a first-of-its-kind, full-structure damage visualization.

Construction of Bridge Cluster Monitoring and Governance Platform with Cross-Platform Multi-Tier Networking Technology

Xin Yan [1], Han Wei [1], and Xiaojing Wang [1]

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Graphical abstract

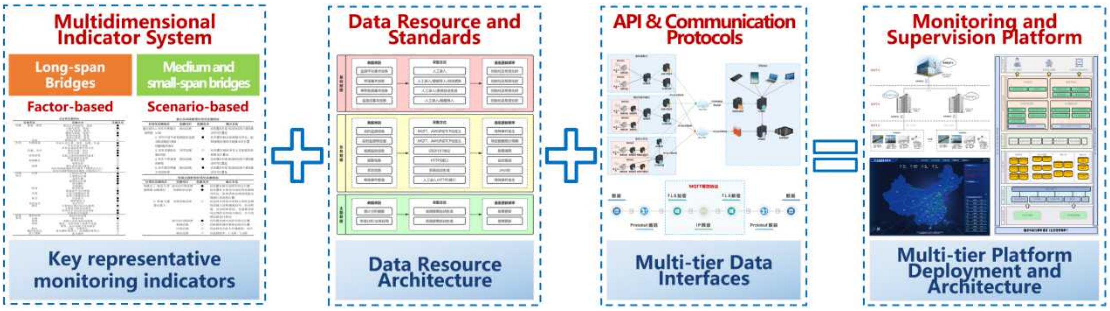

Figure 1 Graphical abstract

1 Objectives and Methodology

The study proposes a multi-tier monitoring and governance platform architecture for bridge clusters. The functional architecture and the resource system architecture are established. Data silos among heterogeneous systems are resolved with clearly defined acquisition methods, update frequencies, and interaction protocols. The study provides unified standards for cross-platform data sharing, including developing standardized data definitions, designing multi-tier platform data interfaces based on REST specifications, standardizing message encoding, data dictionaries, and transport protocols. The challenges of multi-tier platform networking caused by unclear bridge monitoring system architecture, inconsistent data resources, and diverse interface standards are solved.

2 Major results and findings

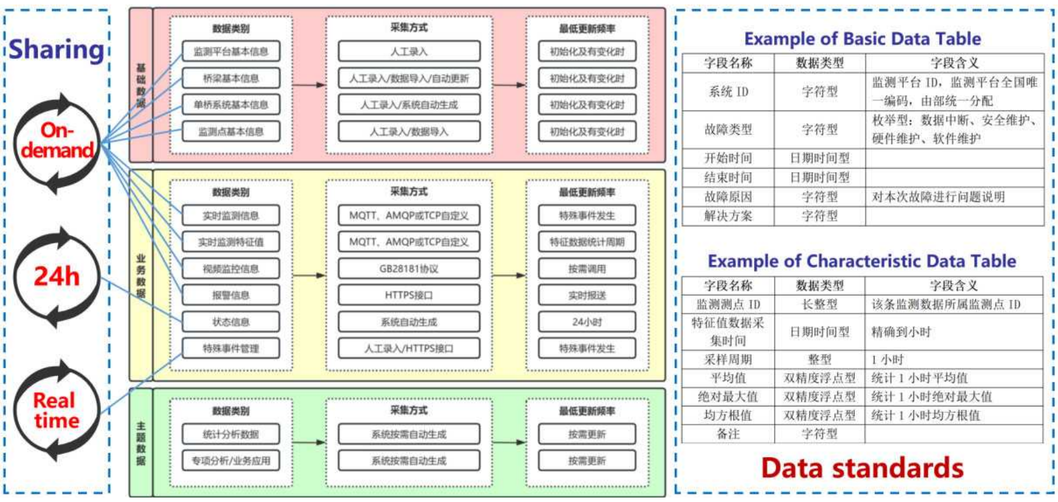

Figure 2 The resource system architecture and data standards

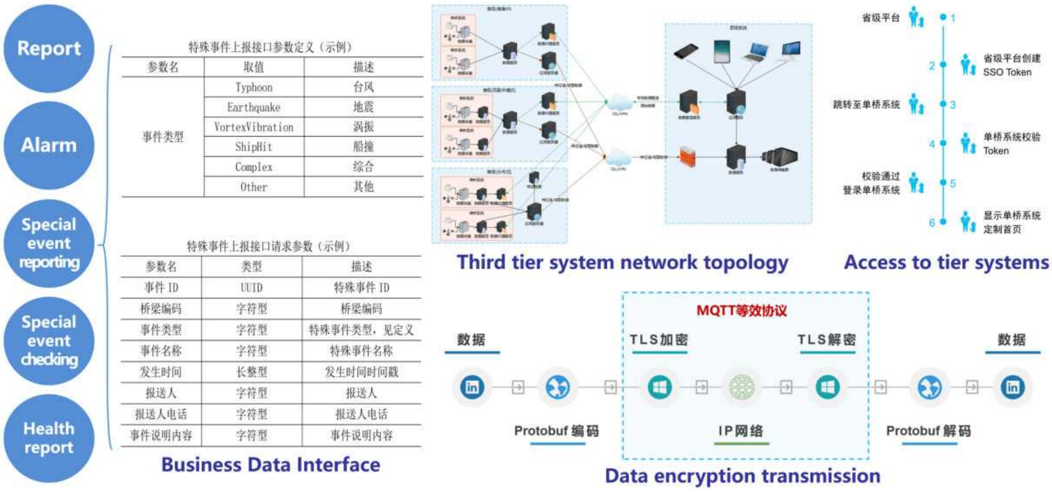

Figure 3 The business data interface of multi tier platform and unified standards

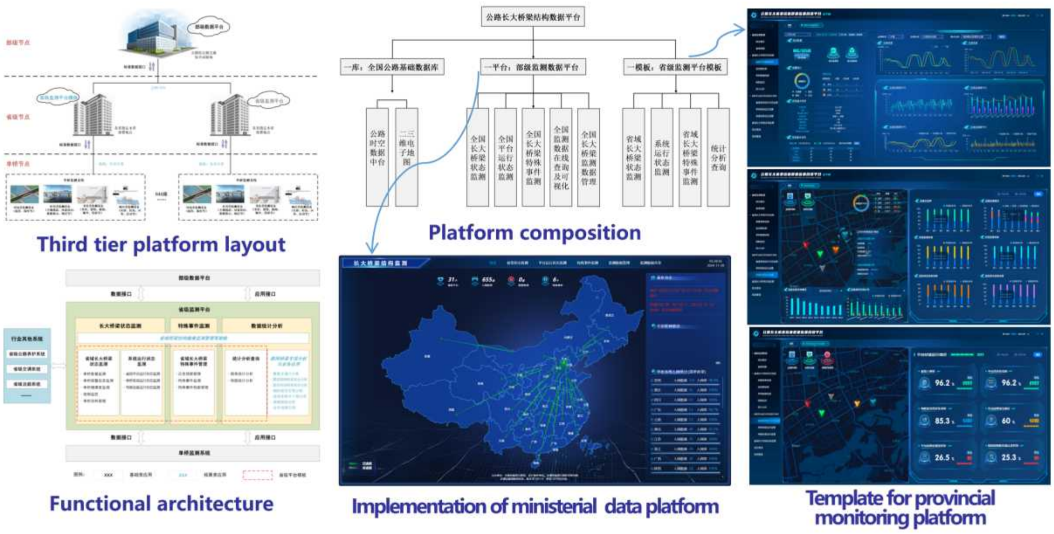

Figure 4 Layout of multi-tier monitoring and Governance platform

Paralel Session B2 Summary:

This session focused on the applications of cutting-edge artificial intelligence (AI) technologies in civil engineering, such as computer vision for structural response measurement, robotic systems for damage detection, large language models for enhancing project management and structural design.

Participants:

- Danhui Dan, Professor, Tongji University
- Yufeng Zhang, Chief Engineer, JSTI Group
- Jiwei Zhong, Deputy director, State Key Laboratory of Bridge Intelligent and Green Construction
- Yongding Tian, Associate Professor, Southwest Jiaotong University
- Xin Yan, Research Fellow, Highway Research Institute of the Ministry of Transport
- Liangfu Ge, Research Assistant Professor, The Hong Kong Polytechnic University
- On-site attendees

1. Large Language Models (LLMs) in Bridge Construction and Maintenance

With the rapid advancement of large language models such as DeepSeek and ChatGPT, new possibilities have emerged for integrating AI-driven question-answering systems into traditional bridge engineering workflows. However, several challenges remain in training domain-specific LLMs for the bridge sector. These include:

- Limited access to high-quality, domain-specific data
- High computational cost of training
- Unstable performance in fine-tuning and downstream tasks

Rather than building dedicated models from scratch, a more practical approach is to leverage general-purpose LLMs to assist decision-making in bridge engineering. Applications may include automated generation of inspection reports, design assistance, and interpreting technical documents to support human experts.

2. Computer Vision and AI for Time-Series, Image, and Point Cloud Analysis

Computer vision and AI technologies have been widely applied in the processing of time-series signals, imagery, and point cloud data for bridge monitoring. However, several pressing issues persist in both research and practical implementation:

- Generalization challenges: Models trained on small or specific datasets often perform poorly when applied to different bridges or conditions.
- Accuracy limitations: Visual inspection under real-world conditions, such as lighting variability or structural occlusion, often leads to suboptimal detection results.
- Lack of interpretability and linkage: Quantifying damage from visual data and linking these detections to the actual structural performance of the bridge remains a theoretical and practical gap.

Future work should focus on developing robust, transferable algorithms and establishing quantitative links between visual indicators and structural integrity.

3. Robotic and Semi-Robotic Platforms in Bridge Inspection

Robotics technologies, including drones (UAVs), unmanned ground vehicles (UGVs), and underwater robots (UUVs), have been increasingly deployed in bridge engineering. However, current applications still largely rely on human operation for navigation and task execution.

The key challenge remains in enabling autonomous decision-making and navigation, especially in complex and dynamic environments. This distinction highlights a divergence between academic research, which often emphasizes autonomy and algorithm development, and engineering practice, which focuses on reliable execution under constraints.

4. Distributed Monitoring Systems for Bridge Networks

Distributed sensing platforms play a vital role in the unified management and maintenance of bridge clusters and road networks. However, practical implementation still faces the following hurdles:

- End-to-end communication reliability: Ensuring efficient and stable communication among distributed nodes remains a technical bottleneck.
- Data quality and transmission efficiency: Maintaining data integrity and minimizing loss or delay in large-scale networks is still an unresolved issue.

Efforts are needed to enhance network protocols, optimize communication architecture, and improve data synchronization mechanisms to support scalable and resilient monitoring solutions.

Paralel Session C1

Topic: Artificial Intelligence Empowered Theory and Methods in Bridge Engineering

Chair: Bin Xu, Lecturer, Zhengzhou University
Cochair: FeiHan, Associate Professor, Northwestem Polytechnical University;
Liangfu Ge, Research Assistant Professor, The Hong Kong Polytechnic University;
Xuewen Yu, Postdoctoral Fellow, Nanyang Technological University;
Danhui Dan, Professor, Tongji University

Introduction:

Artificial intelligence (AI) technologies are gaining increasing attention and application in the field of bridge engineering, spanning the entire life-circle of bridge structures – from design and construction to maintenance and operation. By enabling more sustainable, resilient, and intelligent infrastructure, AI is fundamentally transforming the way we approach modern bridge systems. This session focuses on the emerging intersection between AI and bridge engineering, highlighting recent developments in AI-driven/assisted approaches to structural analysis, optimization design, system identification and health monitoring. We invite contributions that explore innovative theories, methodologies, and applications that demonstrate the transformative potential of AI in addressing complex engineering challenges.

Topics of interest include (but are not limited to):

1. Physics-informed deep learning in structural dynamics
2. AI-driven structural status identification and performance evaluation
3. AI-enabled structural optimization design
4. Intelligent structure design based on generative AI
5. Intelligent monitoring systems for bridge health and safety
6. Integration of digital twins and AI for life-cycle bridge management

Speech:

AI- driven structural operation status and service performance monitoring method

Jun-Qing Lei, Zhong-yu Han, Guo-xin Li, Chengzhong Gui, Zu-Wei Huangei, Haosu Liui, Department of Bridge Engineering, Beijing Jiaotong University

Application of 3D Laser Scanning Technology in Bridge Construction

Dong Liang, Haibin Huang, Yongchen Ling, Lihang Chen, Department of Civil & Transportation Engineering, Hebei University of Technology

Fatigue Crack Detection and Localization in Steel Box Girder using Point Cloud and Image Fusion Machine Vision

Yan Yue, Yu-Fei Liu, Department of Civil Engineering, Tsinghua University

On-line damage detection in cables of cable-stayed bridges from ambient acceleration

Bin Xu, Zirao Wu, and Joan R. Casas, School of Civil Engineering, Zhengzhou University

AI- driven structural operation status and service performance monitoring method

Jun-Qing Lei [1,2], Zhong-yu Han[2], Guo-xin Li [2], Chengzhong Gui [1,3], Zu-Wei Huangei [1,4], Haosu Liui [1,5]

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Graphical abstract:

1 Objectives and Methodology

Objectives and Methods of AI-Driven Monitoring for Structural Operational Status and Service Performance.

(1) Objectives: Real-time anomaly detection, performance degradation assessment, predictive maintenance, and automated decision-making.

① Real time Monitoring&Anomaly Detection: Utilizing AI technology to assess the health status of structures in real-time and identify damages or anomalies in a timely manner.

② Service Performance Evaluation: Analyzing the performance degradation of structures under long-term loads, environmental erosion, and other factors.

③ Predictive Maintenance: Based on data-driven models to predict remaining lifespan and optimize maintenance strategies.

④ Automated Decision Support: Provides intelligent recommendations to enhance structural safety and cost-effectiveness.:

(2) Methods: Multi-sensor fusion, machine learning (e.g., CNN, LSTM), digital twins, computer vision, and probabilistic modeling.

① Sensor Data Fusion: Integrating multiple sources of data such as IoT and wireless sensor networks.

② Machine learning/deep learning models (ML/DL models) - such as CNN, LSTM, GAN, etc., are used for feature extraction and pattern recognition.

③ Digital Twin technology - constructing virtual models to achieve dynamic simulation and state mapping.

④ Computer Vision&UAV Inspection - Automatically identify apparent damages such as cracks and rust.

⑤ Uncertainty Quantification - Combining Bayesian methods to evaluate the reliability of predictions.

2 Major results and findings

2.1 AI-Dri en Wind Resistance Monitoring for Bridges, Key Findings:

(1) AI models (e.g., LSTM, CNN) improved real-time wind response prediction by 20 – 30% compared to traditional methods.

(2) Anomalies (e.g., vortex-induced vibrations) were detected 3 – 5 hours earlier than manual inspections.

Table 1: AI vs. Traditional Methods in Wind Monitoring

Metric	AI-Based Approach	Traditional Methods
Accuracy	95% (ML models)	70 – 80% (Empirical formulas)
Anomaly Detection Time	10 – 30 mins (Real-time)	2 – 6 hours (Periodic checks)
False Alarms	<5% (Deep learning)	(15 – 20)%

Wind Speed vs. Bridge Response(AI Prediction vs. Actual)
=AI+Prediction+vs.+Actual+Data+Trend

AI prediction (blue line) closely matches sensor data (red dots), reducing uncertainty in extreme wind events.

2.2 Railway Bridges: Wind-Seismic-Vehicle-Bridge Coupled Vibration, Key Findings:

(1) AI hybrid models (e.g., Physics-Informed Neural Networks) reduced computational time by 40% for coupled vibration analysis.

(2) Critical Scenarios Identified: Resonance risks under combined wind (⩾20 m/s) and seismic (PGA ⩾0.3g) loads.

(3) Vehicle speed thresholds (e.g., >80 km/h) exacerbating vibrations.

Table2: Dominant Factors in Coupled Vibrations

Factor	Impact Level (1 – 5)	AI Mitigation Suggestion
Wind Load	4	Tuned mass dampers (AI-optimized)
Seismic Load	5	Base isolation + real-time damping
Vehicle Speed	3	Speed limits during extreme events

Peak vibrations occur when wind + seismic + high-speed vehicle loads overlap (AI identifies "red zones").

3. General Discoveries from AI Monitoring

(1) Data-Driven Insights: Corrosion and fatigue cracks progress nonlinearly; AI predicted failure 6 months earlier.

(2) Cost Reduction: Predictive maintenance cut costs by 25% (e.g., avoiding unplanned bridge closures).

(3) Pie Chart: AI Contribution to Safety/Cost Efficiency=AI+Impact+on+Safety+and+Cost

① 45% Early fault detection;
② 30% Maintenance optimization
③ 25% Extended service life

4. Conclusion and Prospect

(1) Bridges under wind: AI enhances real-time response prediction and early anomaly detection.

(2) Railway bridges: AI deciphers complex wind-seismic-vehicle interactions, pinpointing high-risk scenarios.

Overall: AI boosts safety, efficiency, and cost savings by transforming raw data into actionable insights.

Application of 3D Laser Scanning Technology in Bridge Construction

Dong Liang[1], Haibin Huang[1], Yongchen Ling[1], Lihang Chen[1]

[1] Department of Civil & Transportation Engineering, Hebei University of Technology, Tianjin, 300401 China, 13622114075@139.com

Graphical abstract

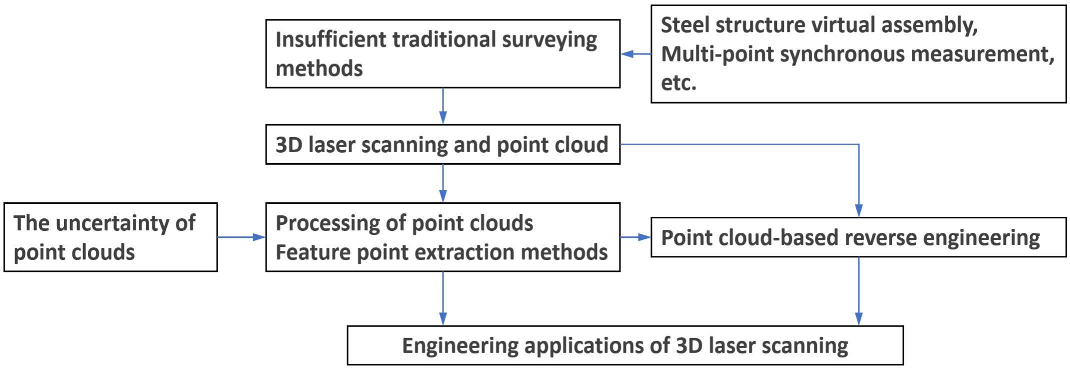

Figure 1 Graphical abstract

Objectives and Methodology

With the increasing scale and complexity of bridge structures, traditional geometric measurement and construction control methods are becoming inadequate in terms of accuracy, efficiency, and safety to meet the high standards of modern bridge construction. Leveraging its advantages of non-contact measurement, high precision, and high efficiency, 3D laser scanning technology is rapidly becoming a key tool for digital construction in bridge engineering. This paper summarizes the typical applications of 3D laser scanning in major projects such as the Yanqing–Chongli Expressway and the G109 New Line Expressway. These applications include virtual assembly, geometric inspection, and bearing jacking, demonstrating the wide applicability and technical advantages of this technology throughout the entire process of bridge construction and maintenance.

During the construction of the steel tower of the Xinglinpu Bridge on the Yanqing–Chongli Expressway, the team addressed the challenges of large segment sizes and high installation accuracy requirements by building a 3D digital model based on high-density point cloud data. Virtual assembly simulations were conducted to pre-check segment positioning deviations and control geometric errors. The results of the virtual assembly directly guided the on-site installation, significantly improving segmental alignment accuracy and construction efficiency while reducing the risks associated with high-altitude operations.

In the assembly of the steel-concrete composite girders for the Xiaowutaishan Bridge on the G109 New Line Expressway, the team dealt with complex structural features such as small curvature and steep longitudinal slope. High-precision point cloud data of the assembly area were captured using 3D laser scanning, and by aligning this data with the design model, assembly errors were analyzed and positioning posture optimized. This ensured high-precision alignment of girder segments in a complex spatial environment and facilitated the implementation of the "prefabrication + digital construction" approach.

During the construction of the Taizicheng Bridge on the Yanqing–Chongli Expressway, the team established a bridge measurement system based on 3D laser scanning that is suitable for cold and high-altitude environments. Addressing the inefficiencies and slow data updates of traditional surveying methods, the system utilized workflows such as multi-station merging, coordinate unification, and structural feature recognition to monitor the spatial positions of tower columns and stay cables, providing data support for structural alignment and precision control.

In addition, to address the challenge of synchronously monitoring the superstructure during the bearing replacement of existing bridges, the team successfully implemented a full-process monitoring scheme based on 3D laser scanning in several projects. For example, in a typical girder bridge project, the 3D shapes of the deck and girder were rapidly acquired at key stages before, during, and after jacking. This enabled millimeter-level monitoring of bearing displacement and analysis of stress trends, helping construction teams to timely optimize operational parameters and effectively avoid risks such as uneven lifting or secondary damage to the structure.

In conclusion, the in-depth application of 3D laser scanning throughout the entire life cycle of bridge construction and maintenance significantly enhances precision control, structural safety assessment, and digital management. In the future, as it continues to integrate with machine vision and digital twin technologies, the application scenarios of 3D laser scanning in bridge engineering are expected to become even more diverse and expansive.

Fatigue Crack Detection and Localization in Steel Box Girder using Point Cloud and Image Fusion Machine Vision

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Graphical abstract

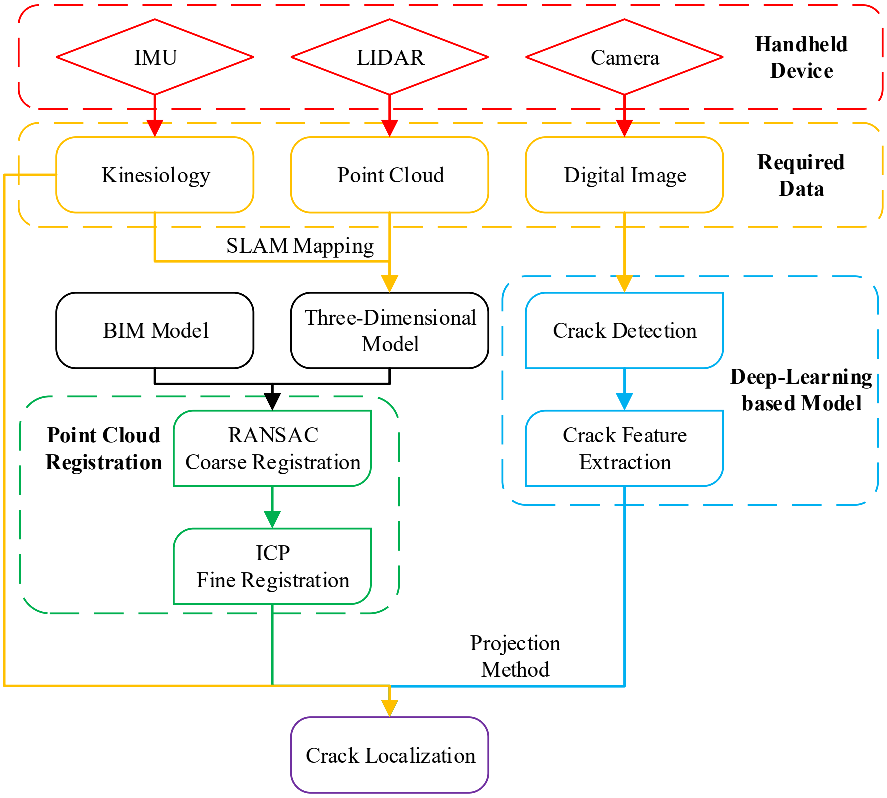

Figure 1 Graphical abstract

1 Objectives and Methodology

The proposed method aims to detect fatigue cracks within steel box girders using computer vision, and to develop a handheld device for data acquisition.

A handheld device with LIDAR, inertial measurement unit (IMU) and camera is designed to collect the necessary visual and kinematic data in the target environment. The acquired point cloud and kinematic data are used in SLAM to generate a point cloud, which is registered with the BIM model to align the reference systems. Digital images are used for crack detection and feature extraction. The crack information is then displayed on the point cloud using projection algorithms for crack localization.

2 Major results and findings

1) A portable visual data acquisition device was designed, which can be carried and operated by personnel to provide accessibility to inspection inside steel box girders.

Figure 2 Design of acquisition device

2) SLAM is introduced into the inspection of steel box girders, addressing the challenge of acquiring GPS signals for localization inside the steel box girders. The data collection for one chamber can be completed within ten minutes.

Table 1 Error of SLAM

Item	Actual measured value(mm)	Measured value on point cloud (mm)	Absolute error (mm)	Relative error
Specimen length	5234.0	5186.2	47.8	0.91%
Specimen width	2398.7	2357.0	41.7	1.74%
Specimen height	1000.0	1018.0	18.0	1.80%
Distance between two cross-partitions	751.2	748.5	2.7	0.36%
U-rib height	295.1	291.8	3.3	1.12%
U-rib spacing	597.9	596.3	1.6	0.27%

3) The localization results of the simulated cracks indicate that the average error is 2.75 mm, with the maximum error not exceeding 5 cm, which demonstrates a good performance in the field of crack localization.

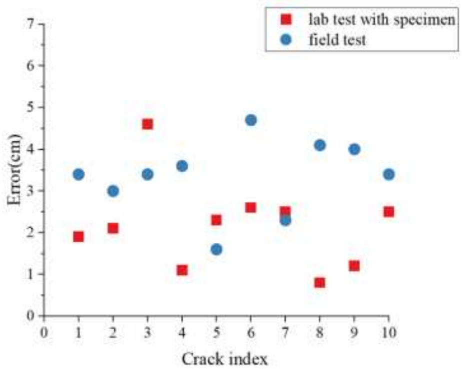

Figure 3 Crack localization error

On-line damage detection in cables of cable-stayed bridges from ambient acceleration

Bin Xu [123], Zirao Wu [1], and Joan R. Casas [2]

[1] School of Civil Engineering, Zhengzhou University, Zhengzhou, 450001, Henan, China, xubin_tmxy@zzu.edu.cn

[2] Department of Civil and Environmental Engineering, Universitat Politecnica De Catalunya, UPC-Barcelona-TECH, Barcelona, 08034, Catalunya, Spain, joan.ramon.casas@upc.edu

[2] Henan Province Engineering Research Center of Safety and Life Extension for Prestressed and Cable Structures, Zhengzhou, 450001, Henan, China

Graphical abstract

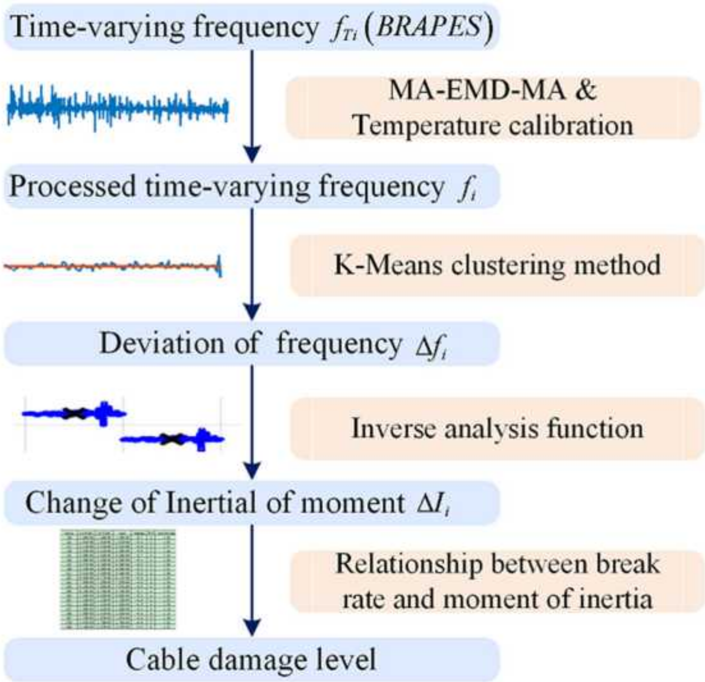

Figure 1 Flowchart of quantitative identification of cable damage

1 Objectives and Methodology

As critical load-bearing components of cable-stayed bridges, cables are essential for their safety. During service, cable tensions change over time due to external dynamic actions such as traffic, temperature, and wind, making it challenging to use cable tension for damage detection. In response, this paper proposes a method for both qualitative and quantitative damage identification of in-service cables based on the time-varying frequency, utilizing the dynamic stiffness theory. To obtain the frequency of in-service cables and remove the influence of traffic and temperature, a combination of the Block-wise Recursive Amplitude and Phase Estimation (BRAPES), Empirical Mode Decomposition (EMD), and Moving Average (MA) methods is employed. First, the cable frequency equation and inverse analysis characteristic function are established based on the dynamic stiffness theory. Then, a simulation method for time-varying frequencies of cables considering traffic loads and temperature effects is proposed based on the cable frequency equation. Using these simulated results, the MA-EMD-MA method for eliminating the influence of external dynamic actions from the time-varying frequencies is developed and validated with real bridge cable data. Finally, using the proposed simulation method, a K-Means Clustering-based qualitative damage identification method is presented, along with a quantitative damage identification strategy based on the cable inverse analysis characteristic function. Therefore, the cable damage identification strategy proposed based on these methods can be used for continuous and long-term real-time qualitative and quantitative identification of damage in in-service cables.

2 Major results and findings

This paper proposes a qualitative and quantitative damage assessment method based on dynamic stiffness theory for cable damage during operation. And the following conclusions are obtained.

(1) In terms of removing the influence of external dynamic loads on frequency, the frequency reconstructed from IMFs outperforms the direct use of the original frequency.

(2) EMD is more effective than EEMD at removing the effects of external dynamic forces on stay-cable frequency. Applying a moving average (MA) prior to both EMD and EEMD not only reduces the number of IMFs and enhances analytical efficiency, but also smooths data fluctuations, thereby delivering superior de-noising performance.

(3) Traffic load and temperature changes do not affect the effectiveness of the cable damage identification method proposed in this paper. The MA-EMD-MA method is not sensitive to temperature changes, but traffic loads will affect fluctuations in processing frequency.

(4) When using K-means clustering to identify damage, the choice of only affects the identification results that contain multiple damage states, and has no impact on that contain only one damage state. Considering that a in-service cable only exhibits two states in a continuous time, it is appropriate to set to 2.

Paralel Session C1 Summary:

This session focused on the effective integration of cutting-edge technologies such as Artificial Intelligence (AI) and 3D Laser Scanning (3DLS) to enhance monitoring efficiency, precision, and intelligence levels, reduce operational costs, and provide more reliable support for bridge maintenance decision-making.

Participants:

- Jun-Qing Lei, Professor, Beijing Jiaotong University
- Dong Liang, Professor, Hebei University of Technology
- Yufei Liu, Associate Research Professor, Tsinghua University
- Bin Xu, Lecturer, Zhengzhou University
- On-site attendees

1. AI-Driven: Automation of Data Processing and Intelligent Upgrading of Bridge Monitoring

(1) Current Status & Challenges

Traditional bridge monitoring systems generate massive data (sensor data, manual inspection records, periodic detection data, etc.). Manual processing and analysis suffer from low efficiency, high costs, and difficulties in real-time identification of subtle changes in potential risks.

(2) AI Application Directions

AI-Driven Infrastructure Monitoring

Machine learning automates sensor data analysis (strain, vibration) to detect micro-structural degradation and issue early warnings, reducing manual workloads. Computer vision processes drone/camera imagery to identify/quantify surface defects (cracks, corrosion), enhancing inspection objectivity and coverage frequency.

Integrated Health Assessment

AI fuses heterogeneous data (sensors, images, point clouds, environmental/historical records) to mine hidden correlations. This constructs holistic bridge "health portraits" for comprehensive condition assessment and predictive maintenance planning, enabling proactive risk management.

2. 3D Laser Scanning: Balancing Efficiency and Accuracy in Point Cloud Data

(1) Technical Challenges & Optimization

3DLS captures high-precision point clouds for digital twins and deformation monitoring but faces massive data volume and efficiency-precision conflicts. Strategies include target-oriented marker placement at critical locations and data volume reduction via localized dense scanning supplemented by low-precision imagery for non-critical areas.

(2) AI-Enhanced Data Processing

AI algorithms denoise point clouds by removing environmental noise (e.g., vehicles, vegetation), automate feature extraction for high-precision auto-registration, and intelligently decimate non-critical areas while preserving key-region accuracy. This balances processing efficiency with measurement fidelity.

3.Multi-Source Heterogeneous Data Fusion: Synergy of Point Cloud Localization and Image Recognition

Point Clouds vs. Images

Point clouds provide precise 3D coordinates for global positioning and geometric measurement, enabling holistic modeling. Images offer rich texture/color information for microscopic defect identification (e.g., cracks, rust) and intuitive interpretation. Both are critical for comprehensive structural assessment.

(2) Fusion Strategy

To overcome imagery limitations (limited field of view, occlusion, and matching ambiguity), point clouds serve as spatial anchors, mapping defects to 3D models. Dual-compatible markers (laser-reflective/camera-contrast) ensure precise alignment and enable AI-based auto-registration for efficient spatial mapping.

4. Future Prospects for AI in Bridge Engineering

High Automation & Unmanned Systems

UAS (LiDAR, HD/IR/multispectral cams) enable autonomous bridge inspections, eliminating high-altitude risks. ROVs perform subsea pier inspections. Smart sensor nodes continuously monitor strain, displacement, and environmental loads. Minimizes manual intervention and establishes comprehensive SHM data foundation.

Predictive Maintenance

DL-based multimodal fusion synthesizes structural data, environmental loads, and maintenance records to forecast component degradation (e.g., cables, bearings). Quantifies deterioration rates, enabling shift from reactive repairs to PdM. Optimizes resource allocation, prevents failures, and extends service life via data-driven planning.

Deep Application of Digital Twins

Real-time monitoring data dynamically updates high-fidelity DT models. Integrates point clouds, BIM, and sensor streams for virtual load simulation, damage evolution analysis, and safety alerts. Enables bidirectional physical-virtual closed-loop decision systems for lifecycle management.

Industry Transformation & Talent Attraction

AI-sensing convergence reshapes civil engineering from labor-intensive to data-driven practices. Attracts cross-disciplinary talent (CS/DS/AI), advancing sustainable infrastructure innovation. Elevates tech profile, fostering a feedback loop: enhanced innovation → high-skilled professionals → resilient intelligent infrastructure.

Parallel Session C2

Topic: Bridge Health Monitoring and Intelligent Operation and Maintenance

Chair: Xiaodong Song, Associate Professor, Southeast University

Cochair: Shizhi Chen, Associate Professor, Chang'an University

Introduction:

Bridges are critical components of transportation infrastructure, and their structural health directly impacts safety, serviceability, and longevity. With increasing traffic loads, environmental effects, and aging structures, there is a growing need for advanced monitoring and intelligent maintenance strategies to ensure bridge reliability and performance. This special session focuses on cutting-edge research and innovative technologies in bridge health monitoring and intelligent operation and maintenance, aiming to enhance structural safety, optimize maintenance strategies, and extend service life. The session will provide a platform for researchers and engineers to present and discuss the latest advancements in sensor technologies, data analytics, artificial intelligence (AI), and digital twins for bridge health assessment and predictive maintenance. Contributions addressing real-world challenges, case studies, and novel methodologies are highly encouraged.

The following topics will be shown in this session, including but not limited to:

- Data-driven and AI-based damage detection and condition assessment
- Digital twin and cyber-physical systems for bridge management
- Remote sensing and UAV-based inspection techniques
- Predictive maintenance and life-cycle cost optimization
- Real-time monitoring and early warning systems
- Other related topics

Speech:

Computer vision based bridge surface damage recognition under limited supervision

Yang XU, Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology,

Bridge Operational Modal Analysis Considering Excitation Variations

Yi-Chen Zhu, Zi-Yu Guan, Department of Bridge Engineering, School of Transportation, Southeast University

Dynamic Characterization Model of Lateral Coordination Performance for Prefabricated Beam Bridges Based on Vehicle-Induced Response Mapping Analysis

YANG Gan, CHEN Shi-zhi, School of Highway, Chang'an University

Eliminating the effects of temperature and vehicle interference on modal frequency identification based on autoencoders with particle swarm optimization backpropagation

Xiaodong Song, Wenxin Yu[1], C.S. Cai, School of Transportation, Southeast University,

Computer vision based bridge surface damage recognition under limited supervision

Yang XU[1,2]

[1] Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin 150090, China, xyce@hit.edu.cn

[2] School of Civil Engineering, Harbin Institute of Technology, Harbin, 150090, China

Graphical Abstract

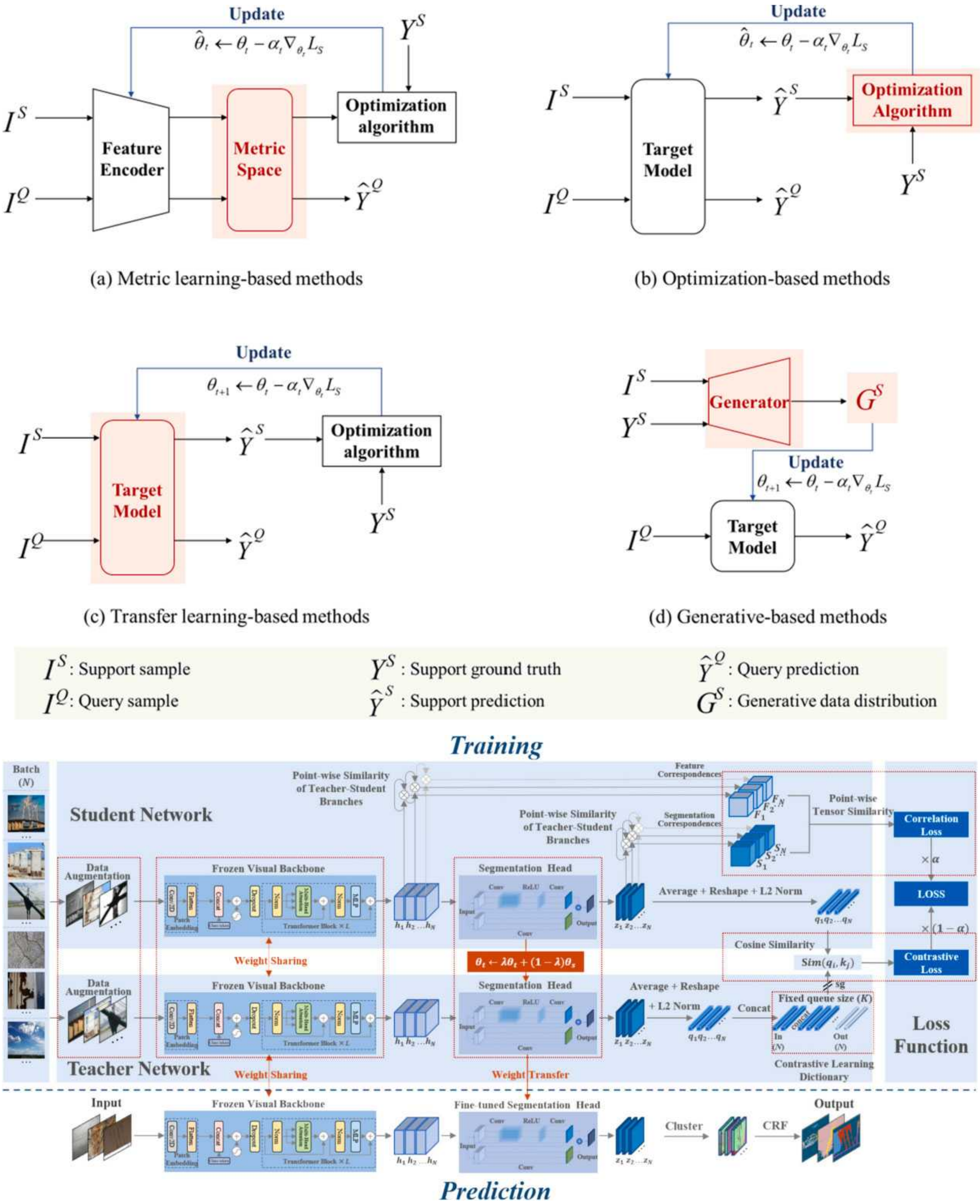

Figure 1 Graphical abstract

Objectives and Methodology

The successful development of computer vision and deep learning techniques has recently revolutionized structural health monitoring for bridges. Data-driven models are established to map the relationships between inputs and outputs and dig out embedded structural behaviors and implicit physical mechanisms. However, the model performance highly relies on the extensive amount and diversity, intra-class completeness, and inter-class balance of training data, and the generalization ability on scarce data with specific features and particular patterns is challenging under real-world scenarios. This talk aims to discuss computer vision based bridge surface damage recognition under limited supervision. First, a unified mathematical framework of few-shot learning is formulated with error analysis. Next, a taxonomy of metric learning-based, optimization-based, transfer learning-based, and generative model-based methods is summarized with the corresponding applications of structural damage recognition following a small-data regime. Then, a transformer based large vision model for universal structural damage segmentation is established. A self-supervised correlation learning procedure is designed to ensure cross-level feature alignment without pixel-level annotations, and a contrastive learning strategy is designed to learn intra-instance similarity and inter-instance separability. Finally, the proposed methods are validated on multi-scale image datasets for cable-supported and concrete bridges. Briefly introduce the aims and methodology of this research.

Bridge Operational Modal Analysis Considering Excitation Variations

Yi-Chen Zhu [1] and Zi-Yu Guan [1]

[1] Department of Bridge Engineering, School of Transportation, Southeast University, Nanjing, 211189 China, zhuyichen@seu.edu.cn

Graphical abstract

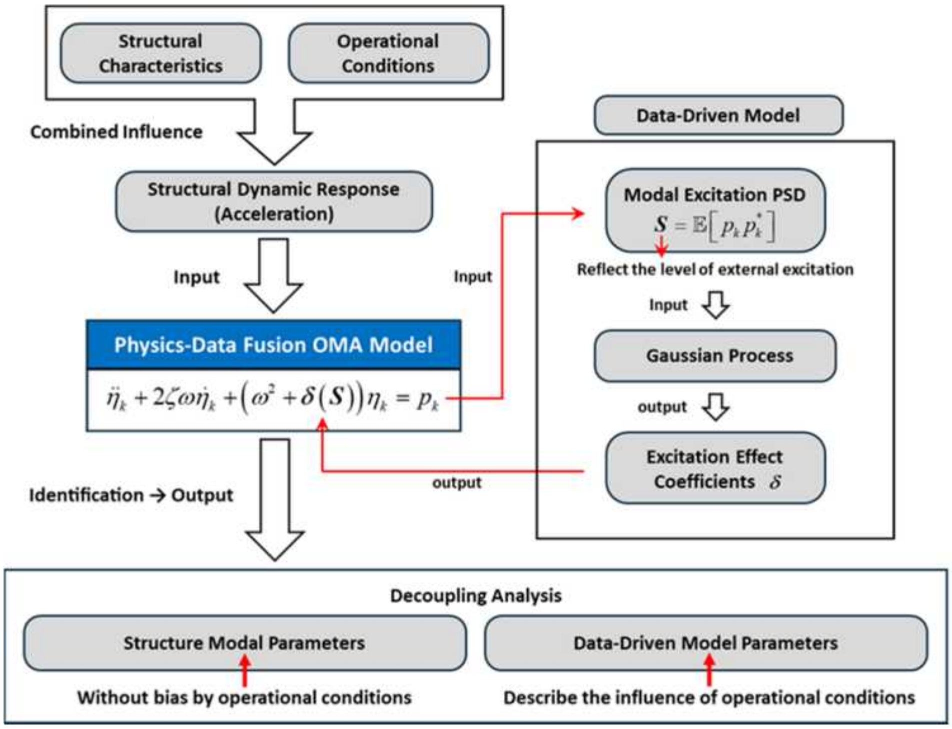

Figure 1 Graphical abstract

1 Objectives and Methodology

Operational modal analysis (OMA) is extensively used in long-term structural health monitoring (SHM) to identify the dynamic characteristics of structures under working conditions. However, external excitations like wind and traffic loads have a significant effect on the structure dynamic properties. Conventional OMA methods typically process structural dynamic responses using only the structural dynamic model, without accounting for variations induced by external excitations. As a result, the modal parameter estimates are biased in this case.

To address this issue, this paper proposes a Bayesian OMA method integrating structural dynamic model with Gaussian Process (GP) to identify the dynamic properties of structures while capturing the effect due to excitation variations at the same time. Recognizing the impracticality of directly measuring external excitations such as vehicular loads and wind forces, this study employs modal force power spectral densities as indirect indicators of excitation intensity. The GP uses the identified power spectral densities as inputs, and a latent function is proposed to capture the relationship between variations in external excitations and their effects on dynamic properties. By embedding latent variables in structural dynamic model, the proposed method systematically suppresses biases induced by external excitation variations. Thanks to the proposed framework, this method enables both physical interpretability and the flexibility to capture the nonlinear interactions between external excitations and structural modal parameters under varying excitation conditions.

The method's theoretical formulations are derived by employing variational inference in conjunction with the Laplace approximation. Variational inference enables the approximation of the latent variables' posterior distribution as a Gaussian. The Laplace approximation then provides more accurate local probabilistic estimates. These two techniques mitigate the computational challenges associated with high-dimensional integrations while providing refined local probabilistic estimates. In the proposed method, an Expectation-Maximization (EM) method is used to effectively identify the dynamic properties as well as the hyperparameters of the GP model. Collectively, these techniques reduce computational complexity, improve convergence rates, and enhance the accuracy of parameter identification.

2 Major results and findings

The proposed method is validated using two examples. The first example employs multi-segment synthetic vibration datasets generated from a state-space model to validate the accuracy and robustness of the proposed method. Compared with conventional OMA methods, the proposed method delivers reduced bias and tighter uncertainty bounds in modal parameter identifications. Most of these estimates fall within their 95% confidence intervals and closely align with observed trends. The second example uses in-situ data from the Ma'anshan Yangtze River Bridge to validate that the proposed method enhances the applicability of modal parameter identification under variable excitation conditions, demonstrating its robustness for long-term SHM applications.

Despite these accomplishments, several limitations should be further investigated. The proposed method solely addresses the structural sensitivity of natural frequencies to external excitations, while effects on damping ratios and mode shapes have not been thoroughly explored. Although the computational complexity is reduced by decomposing the target parameters into two independent objective functions, additional optimization efforts are required to further improve both accuracy and computational efficiency. Future work will address these issues by refining the underlying model assumptions and incorporating multi-sensor data fusion techniques. Furthermore, integrating Digital Twin technology into the physics-data fusion framework via virtual modeling and continuous monitoring offers significant potential for real-time dynamic simulation, predictive assessment, and comprehensive structural health evaluation.

Dynamic Characterization Model of Lateral Coordination Performance for Prefabricated Beam Bridges Based on Vehicle-Induced Response Mapping Analysis

YANG Gan[1], CHEN Shi-zhi[1]

[1] School of Highway, Chang'an University, Xi 'an 710064, China, ygchd@chd.edu.cn

Graphical abstract

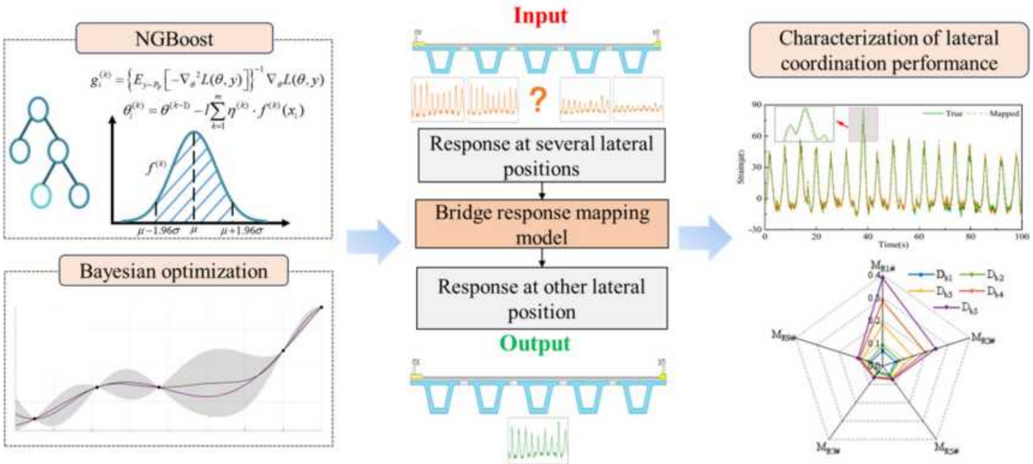

Figure 1 Graphical abstract

1 Objectives and Methodology

The lateral response distribution relationship of a bridge under load is a key indicator of its lateral coherence performance. The classical lateral load distribution factor reflects the distribution relationship of the bridge's lateral response under static load at a specific location. However, in practice, the vehicle loading position is highly random and the vehicle-induced response exhibits significant dynamic characteristics. To quickly understand the lateral response distribution characteristics of a bridge without interrupting traffic, this paper proposed a spatial lateral response mapping model for prefabricated bridges based on the Bayesian optimization NGBoost algorithm. In this model, the NGBoost algorithm with Bayesian optimization was used to learn the time-varying nonlinear mapping relationship between the spatial lateral responses of a prefabricated slab bridge under different random traffic conditions, mapping known responses at several locations to unknown responses at other locations.

2 Major results and findings

The effectiveness of the proposed method was tested. The results showed that Bayesian Optimization NGBoost certain outperformed standard NGBoost and Long Short-Term Memory (LSTM) networks in terms of accuracy and robustness. Under typical conditions, its average coefficient of determination (R^2) reached 0.986, which was 4.4% and 36.4% higher than that of standard NGBoost and LSTM, respectively. In the emergency lane region, where data was sparse, the method still achieved a high R^2 of 0.953, while LSTM only reached 0.374. Numerical simulations were conducted to analyze various combinations of different road surface roughness levels and traffic densities. The deflection response achieved an R^2 above 0.951, and the root mean square error (RMSE) was below 0.153 mm. In addition, the model can locate the damage position of transverse connections and assess the severity of the damage by analyzing the distribution characteristics and magnitude of the prediction errors. In practical monitoring scenarios, the strain responses mapped by the model achieved an R^2 above 0.981 and an RMSE below 2.381 με, with actual values mostly falling within the 95% confidence interval. These results demonstrate that the proposed method not only accurately captures the time-varying mapping relationship of the bridge's transverse response, but also enables the localization and assessment of damage in transverse connections, thereby supporting the dynamic evaluation of the transverse cooperative performance of prefabricated beam bridges under uninterrupted traffic conditions.

Eliminating the effects of temperature and vehicle interference on modal frequency identification based on autoencoders with particle swarm optimization backpropagation

Xiaodong Song[1], Wenxin Yu[1], C.S. Cai[1]

[1] School of Transportation, Southeast University, Nanjing, 211189 China, xdsong@seu.edu.cn

Graphical abstract

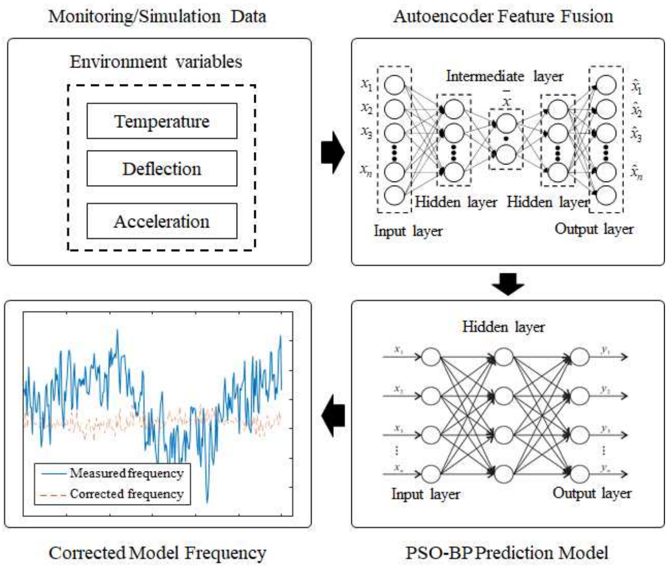

Figure 1 Graphical abstract

1 Objectives and Methodology

Accurate identification of modal frequencies from bridge monitoring data is a cornerstone of reliable structural health evaluation. However, these frequencies are substantially influenced by external factors, especially ambient temperature variations and vehicle loads, which can mask or mimic the dynamic signatures of structural damage. This study proposes a robust, data-driven methodology to simultaneously eliminate the confounding effects of both temperature and vehicular interference in modal frequency identification.

The methodological framework is built on a hybrid neural network model that combines an autoencoder (AE) and a Particle Swarm Optimization–Backpropagation (PSO-BP) algorithm. Multi-source structural health monitoring (SHM) data—including vertical acceleration, mid-span deflection, and temperature—are fed into an AE, which performs nonlinear feature extraction and dimensionality reduction. The resulting latent variables capture the essential dynamic characteristics of the structure while decoupling the temperature and vehicle-induced responses. These low-dimensional features are then used as inputs for the PSO-optimized BP neural network, which is trained to predict modal frequencies identified by stochastic subspace identification techniques.

To ensure model generalizability, both numerical simulations (vehicle–bridge interaction with varied temperature and traffic parameters) and real-world bridge SHM datasets are utilized for model training and validation. The corrected modal frequencies are derived by comparing predicted values under arbitrary operational conditions against a baseline state (reference temperature and no traffic), thereby quantifying and removing the coupled environmental effects. This enables the corrected modal frequencies to reflect intrinsic structural properties independent of transient environmental or operational variability.

2 Major results and findings

The proposed AE-PSO-BP approach demonstrates a marked improvement in the stability and reliability of modal frequency identification. Simulation results reveal that, after correction, the standard deviation and coefficient of variation (CV) of both first- and third-order modal frequencies are reduced by more than 85% relative to the uncorrected values. For example, the first-order frequency's CV decreased from 13.0% (measured) to 1.37% (corrected), and the third-order CV dropped from 44.0% to 4.56%. In field applications using actual bridge SHM data, similar performance is observed: the first-mode CV is reduced from 2.29% to 0.09% post-correction. Table 1 summarizes the key statistics for both simulated and measured cases.

Table 1 Statistical Characteristics of Modal Frequencies Before and After Correction

Mode	Frequency Type	Max (Hz)	Min (Hz)	Std. Deviation	CV
1st	Measured	4.11	3.93	0.0355	0.1300
1st	Corrected	4.06	3.98	0.0117	0.0137
3rd	Measured	4.90	4.55	0.0664	0.4400
3rd	Corrected	4.81	4.68	0.0214	0.0456

Time-series analysis further illustrates that the corrected frequencies exhibit minimal fluctuation under variable temperature and traffic loads, effectively eliminating both seasonal and short-term trends that previously masked true structural changes. As a result, the corrected modal frequencies serve as robust indicators for bridge condition assessment. For instance, the application of technical evaluation criteria based on the corrected frequencies resulted in high dynamic characteristic scores, confirming the structural integrity of the case study bridge despite pronounced environmental variability in the raw data.

The model's efficacy is consistently validated across simulated and real SHM datasets, highlighting its applicability to practical bridge health monitoring scenarios. The integrated AE-PSO-BP framework thus enables the extraction of genuine structural information from noisy monitoring data, substantially reducing false-positive or masked-negative diagnoses associated with environmental confounders. The approach is adaptable and can be further extended to incorporate additional environmental or operational factors, thereby offering a scalable solution for next-generation SHM systems.

Paralel Session D1

Topic: Intelligent Transportation and Smart Highway

Chair: Songtao Lv, Professor, Changsha University of Science and Technology
Cochair: Wei Hao, Professor, Changsha University of Science and Technology
Speech:
New Advances in Digital Simulation Technology for Urban Transportation Systems: Development of the TranStar Traffic Large Model
Gang Ren, Professor, Southeast University
Intelligent Road Markings for Radar Perception and Structure Monitoring
Dawei Wang, Professor, Harbin Institute of Technology
Conductive and Wave-absorptive Asphalt Pavement Based on Nano-Carbon Coating of Aggregate
Zhen Leng, Professor, The Hong Kong Polytechnic University
Digital-Driven and AI-Powered: Key Technologies and Practical Explorations in the Operational Transformation of Capital Highways
Hao Sun, Deputy General Manager, Yunxingyu Traffic Technology LTD., Beijing, China
Key Technologies for Smart Road Construction, Operation and Maintenance
Dongdong Ge, Professor, Changsha University of Science and Technology
Low-Cost and High-Performance Digital Twin Technology for Highways
Wei Hao & Kefu Yi, Changsha University of Science and Technology

Paralel Session D2

Topic: Autonomous Driving and Vehicle-Infrastructure Cooperation

Chair: Daxin Tian, Professor, Beihang University
Cochair: Chunmian Lin, Assistant Professor, Beihang University
loV-enabled Vehicle-Road-Cloud Sensing-Communication-Control Integration

Introduction:

This conference is supported by the the National Key Research and Development Program of China (No. 2022YFC3803700), aiming to break through the core challenges and technology bottlenecks for intelligent transportation system and smart city. This session would deeply investigate cutting-edge technologies of autonomous driving and vehicle-infrastructure cooperation, including but not limited to multi-modal fused perception, prediction, planning and decisionmaking, end-to-end autonomous driving, vision-language-(action) world model, out-of-distribution, multi-agent cooperation, internet of vehicle, edge computing, etc. Besides, this session will further explore several practical implementation in the closed campuse or specific scenario, and also discuss future prospects and directions for technology deployment.

This conference cordially invites scientists, professionals and engineers from both academia and industry to participate together, and collaborates in dvancing fundamental research, technological innovation, and engineering applications towards high-level autonomous driving,vehicle-infrastructure cooperation, and intelligent transportation system.

Speech:

loV-enabled Vehicle-Road-Cloud Sensing-Communication-Control Integration Key Technology and Applicatior Practice

Jianshan Zhou, School of Transportation Science and Engineering, Beihang University

Constructing Autonomous Driving World Models Through Uncertainty Reduction

Chen Min, Institute of Computing Technology

Research and Application of Key Technologies for Intelligent Perception of Urban Rail Trains

Zhangyu Wang,School of Transportation Science and Engineering

Intelligent and Streamlined Machine Network for Vehicle-Road Collaboration

Guiyang Luo, School of Computer Science, Beijing University of Posts and Telecommunications

Research on 3D Perception Technologies Driven by Representation Decoupling

Xiaoyan Li, School of Information Science and Technology, Beijing University of Technology, Beijing University of Technology

Intelligent and Streamlined Machine Network for Vehicle-Road Collaboration

Guiyang Luo, School of Computer Science, Beijing University of Posts and

Telecommunications

Multi-Sensor Data Fusion Perception for Connected and Autonomous Vehicles

Chunmian Lin, School of Transportation Science and Engineering, Beihang University, Beijing,

Key Technology and Applicatior Practice

Jianshan Zhou [1]

[1] School of Transportation Science and Engineering, Beihang University, Beijing, 102206 China, jszhou@buaa.edu.cn

Graphical abstract

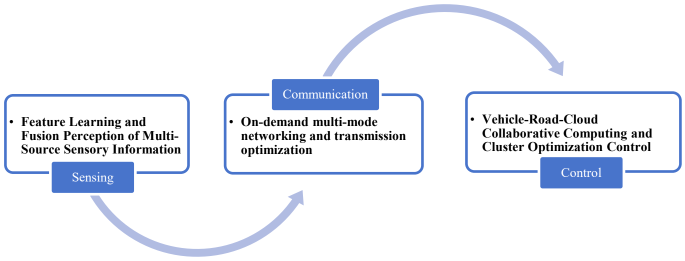

Figure 1 Graphical abstract

1 Objectives and Methodology

ICV Commercialization Faces Three Key Constraints in Industrial Scaling: Single-Vehicle Perception Insufficiency, Single-Mode Communication Instability, and Single-Node Control Suboptimality. To address the aforementioned challenges, we explore solutions from three perspectives: Sensing, Communication, and Control:

(1) How to enhance environmental perception accuracy, robustness, and generalization capabilities;

(2) How to mitigate large-scale contention for network resources;

(3) How to achieve reliable orchestration of computing resources across the vehicle-infrastructure-cloud architecture.

At the perception level, we focus on feature learning and fusion perception of multi-source sensory information:

(1) Leveraging Gaussian Mixture Models (GMM) and Expectation-Maximization (EM) algorithms, we develop methodologies for anomalous sensor identification and missing data inference;

(2) Building upon information theory and multi-agent collaboration frameworks, we propose a distributed global information fusion perception approach;

(3) By embedding multi-source perceptual features from air-space-ground terminals into textual feature spaces, we achieve cognitive-level fusion and decision-making for integrated aerial-terrestrial features.

At the transmission level, we focus on on-demand multi-mode networking and transmission optimization:

(1) Proposing a resource orchestration framework based on evolutionary game theory with channel congestion pricing;

(2) Developing a bio-inspired self-organizing network model incorporating dynamic adaptive multi-hop routing;

(3) Establishing a communication-computation co-optimization framework with coupled reliability awareness and Nash equilibrium-based computation offloading for large-scale vehicular-edge-cloud systems.

At the control level, we focus on vehicle-road-cloud collaborative computing and cluster optimization control:

(1) Integrating information theory with Dynamic Voltage Scaling (DVS) technology, we establish a reliability evaluation model for air-ground communication and computation, developing an optimal task partitioning strategy and collaborative framework for air-space-ground clusters;

(2) Revealing the impact of stochastic spacing and heterogeneous communications on platoon safety, thereby laying theoretical foundations for cooperative control;

(3) Addressing air-space-ground cluster coordination through a Min-Max robust optimization algorithm, we design a robust peer optimization model and formation control method using semidefinite relaxation transformation.

2 Major results and findings

We have developed a suite of vehicle-road-cloud integrated sensing and transmission technologies and equipment with independent intellectual property rights, including LTE-V/DSRC multi-mode OBU/RSU units, edge computing server components, edge signal optimization controllers, and in-vehicle computing terminals. These innovations were successfully implemented in the Ministry of Science and Technology-supported "Intelligent Collaboration" major project, enabling critical applications such as intelligent connected vehicle decision-making, air-ground collaborative measurement and control, and three-dimensional traffic guidance systems.

Table 1 Results and Application

Constructing Autonomous Driving World Models Through Uncertainty Reduction

Chen Min [1]

[1] Institute of Computing Technology, Chinese Academy of Sciences, Beijing, 100190 China, minchen@stu.pku.edu.cn

Graphical abstract

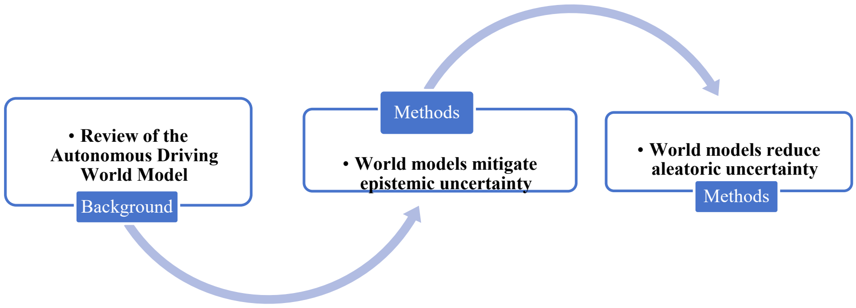

Figure 1 Graphical abstract

1 Objectives and Methodology

Autonomous driving systems confront significant uncertainties, which are primarily classified into two categories: epistemic uncertainty and aleatoric uncertainty. Epistemic uncertainty pertains to the current state, arising from incomplete knowledge due to insufficient information (e.g., occlusions or glare). Aleatoric uncertainty concerns future states, stemming from the inherent randomness of the physical world that cannot be fully eliminated.

World Models possess the capability to simultaneously mitigate both epistemic and aleatoric uncertainty. For current states, they estimate imperceptible information to reduce epistemic uncertainty. For future states, they predict plausible environmental conditions to diminish aleatoric uncertainty. Furthermore, predictive uncertainty constitutes an aggregate manifestation of epistemic and aleatoric uncertainties.

To mitigate epistemic uncertainty, we address limitations in existing perception methods where 2D images lack 3D spatial structural information and depth estimation only captures object surface features. We propose 3D scene reconstruction-based pre-training for 2D imagery using occupancy grid representations to reduce epistemic uncertainty. Specifically, we introduce UniScene—a unified pre-training framework for surround-view cameras—featuring an auxiliary occupancy grid prediction task. This approach enables models to master 360 scene geometry priors during pre-training, while leveraging massive paired image-LiDAR datasets to fully exploit 3D spatial information through reconstruction-based 2D image pre-training.

To reduce aleatoric uncertainty, we propose a 4D spatiotemporal pre-training framework based on World Models. This incorporates an auxiliary World Model task that enables models to acquire 3D scene reconstruction and future prediction capabilities during pre-training. We further introduce a Memory State-Space Model for decoupled spatiotemporal modeling and design adaptive Task Prompts to extract task-specific information.

2 Major results and findings

Experimental results on the nuScenes dataset demonstrate that our scene reconstruction-based 2D image pre-training model improves 3D object detection performance by approximately 2% mAP, as detailed in Table 1. The proposed world model-based 4D spatiotemporal representation learning framework significantly enhances end-to-end autonomous driving performance in planning tasks (Table 2), effectively reducing aleatoric uncertainty in autonomous navigation.

Table 1 3D Object Detection Performance on nuScenes Validation Set

类型	方法	预训练	网络骨干	图像大小	CBGS	mAP↑	NDS↑	mATE↓	mASE↓	mAOE↓	mAVE↓	mAAE↓
Transformer[99]	DETR3D[99]	FCOS3D[212]	R101-DCN	900×1600	✓	0.349	0.434	0.716	0.268	0.379	0.842	0.200
	DETR3D[99]	UniScene	R101-DCN	900×1600	✓	**0.360**$^{+1.1\%}$	**0.461**$^{+2.7\%}$	**0.701**	**0.260**	**0.372**	**0.730**	**0.188**
	BEVFormer[79]	FCOS3D[212]	R101-DCN	900×1600	×	0.416	0.517	0.673	0.274	0.372	0.394	0.198
	BEVFormer[79]	UniScene	R101-DCN	900×1600	×	**0.438**$^{+2.2\%}$	**0.534**$^{+1.7\%}$	**0.656**	**0.271**	**0.371**	**0.348**	**0.183**
LSS[103]	BEVDet[82]	ImageNet[11]	R-50	256×704	×	0.286	0.372	0.724	0.278	0.590	0.873	0.247
	BEVDet[82]	UniScene	R-50	256×704	×	**0.310**$^{+2.4\%}$	**0.395**$^{+2.3\%}$	**0.701**	**0.259**	**0.578**	**0.852**	**0.230**
	BEVDepth[196]	ImageNet[11]	R-50	256×704	×	0.351	0.475	0.639	0.267	0.479	0.428	0.198
	BEVDepth[196]	UniScene	R-50	256×704	×	**0.376**$^{+2.5\%}$	**0.492**$^{+1.7\%}$	**0.620**	**0.259**	**0.466**	**0.425**	**0.187**

Table 2 Planning Task Performance on nuScenes Validation Set

方法	L2(m)↓				Col.Rate(%)↓			
	1s	2s	3s	Avg.	1s	2s	3s	Avg.
FF[281]	0.55	1.20	2.54	1.43	0.06	0.17	1.07	0.43
EO[282]	0.67	1.36	2.78	1.60	0.04	0.09	0.88	0.33
ST-P3[280]	1.33	2.11	2.90	2.11	0.23	0.62	1.27	0.71
BEVGPT[283]	0.39	0.88	1.70	1.22	-	-	-	-
GPT-Driver[284]	0.21	0.43	0.79	0.48	0.16	0.27	0.63	0.35
UniAD[83]	0.48	0.96	1.65	1.03	0.05	0.17	0.71	0.31
+ OccNet[197]	0.49	0.95	1.64	1.02	0.07	0.15	0.69	0.30
+ UniScene[256]	0.47	0.91	1.56	0.98	0.05	0.16	0.64	0.28
+ BEVDistill[213]	0.46	0.92	1.60	0.99	0.05	0.16	0.67	0.29
+ **DriveWorld**†	$0.47^{-0.01}$	$0.86^{-0.10}$	$1.42^{-0.23}$	$0.92^{-0.11}$	0.05	$0.13^{-0.04}$	$0.59^{-0.12}$	$0.26^{-0.05}$
+ **DriveWorld**‡	$\mathbf{0.34}^{-0.14}$	$\mathbf{0.67}^{-0.29}$	$\mathbf{1.07}^{-0.58}$	$\mathbf{0.69}^{-0.34}$	$\mathbf{0.04}^{-0.01}$	$\mathbf{0.12}^{-0.05}$	$\mathbf{0.41}^{-0.30}$	$\mathbf{0.19}^{-0.12}$

Research and Application of Key Technologies for Intelligent Perception of Urban Rail Trains

Zhangyu Wang [1]

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Graphical abstract

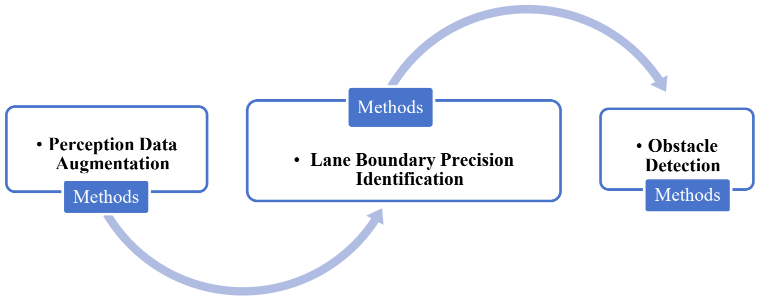

Figure 1 Graphical abstract

1 Objectives and Methodology

Addressing risks of frequent rail accidents caused by complex operational environments and extended train braking distances, this research focuses on developing all-weather long-range intelligent perception technologies for urban rail transit. Critical perception capabilities requiring urgent solutions include: all-weather detection in rain/snow conditions, precise rail zone monitoring, and ultra-long-range forward perception.

In the field of all-weather perception, we tackle critical research difficulties including substantial data noise during rain/snow conditions and limited data features under complex lighting. Our approach explores diffusion model-based denoising techniques, developing an integrated image enhancement pipeline for simultaneous rain/snow/fog removal and low-light enhancement. Additionally, to resolve sparse point cloud data at long distances, we introduce an image-fusion completion technology. Leveraging a stacked hourglass architecture, achieving dense depth completion for 300m scenarios.

In the field of precise track clearance identification, we have addressed the challenge of interlaced tracks in switch areas by developing a vision-based 2D track line detection method, achieving reliable track region recognition in complex scenarios. Additionally, to overcome the difficulty of clearance identification caused by variable track gradients, we proposed a vision-based 3D track clearance detection approach, which has achieved long-range identification exceeding 300 meters.

In the field of track obstacle detection, we addressed the challenges of significant scale variations and long-distance obstacles by proposing a frustum projection-based 3D object detection method, achieving detection capabilities over 400 meters in the forward direction. Furthermore, to overcome the bottleneck of detecting irregularly shaped obstacles, we introduced a spatial grid representation-based obstacle detection approach, enabling generic obstacle detection.

2 Major results and findings

Figure 2 demonstrates the effectiveness of the 2D track region detection and obstacle detection methods. Furthermore, through in-depth collaboration with domestic companies, we have advanced the industrial application of our technology. The resulting systems have been deployed in engineering applications across 29 lines in 10 cities nationwide. Implemented on over 400 trains with more than 1,000 units installed, the integrated forward-facing environmental perception algorithm has successfully obtained compliance certification to the European Standard EN 50129:2018 for railway functional safety.

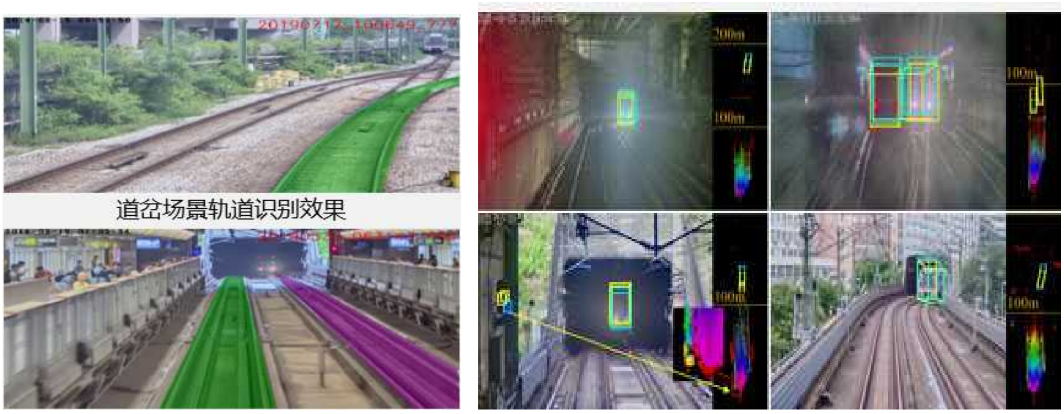

Figure 2 2D 轨道区域检测和障碍物检测效果

Intelligent and Streamlined Machine Network for Vehicle-Road Collaboration

Guiyang Luo [1],

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Graphical abstract

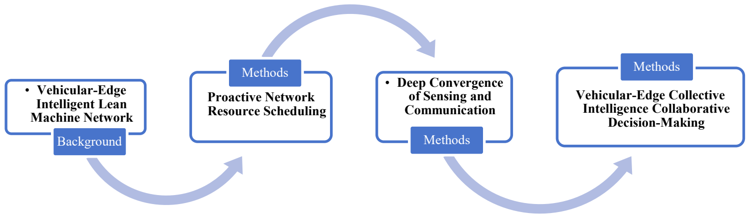


Figure 1 Graphical abstract

1 Objectives and Methodology

With the integration of new AI-enabled vehicular, roadside, and cloud-based systems—including autonomous vehicles, roadside perception units, intelligent traffic signal controls, and traffic command systems—transportation infrastructure is rapidly evolving from human-centric digital frameworks into large-scale machine collectives for artificial intelligence. This report presents our research group's recent advances in intelligent machine networks, encompassing: proactive network resource scheduling, perception-communication co-design, and efficiency-driven collaborative decision-making for vehicle-road collectives.

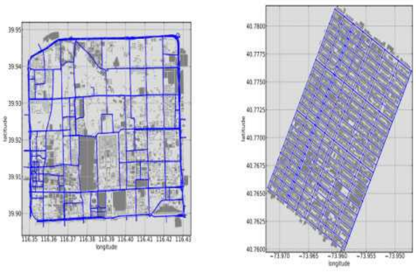
For proactive network resource orchestration in Vehicular-Edge Intelligent Lean Machine Networks, we proposed a deep learning-based 4G QoS assurance algorithm. This approach utilizes deep learning to capture the complex interdependencies among user attributes, transmitted data characteristics, and base station conditions. By modeling these relationships, the algorithm predicts user network performance variations under different base station conditions and across diverse data transmission scenarios.

In advancing the deep convergence of sensing and communication, we investigated multi-vehicle-road collective intelligence collaborative cognition, integrating individual perception with intelligent machine language. We proposed a mid-level feature collaboration-based approach for multi-vehicle cooperative perception and resource allocation. This enables base stations to perform global resource orchestration by matching sensor coverage gaps across vehicles, thereby achieving maximized utilization, maximized system benefit, and minimized conflict.

For vehicular-edge collective intelligence collaborative decision-making, we addressed key challenges including heterogeneous vehicle-road entities, spatio-temporal action coupling, and large state spaces by proposing an evolutionary game-based collaborative traffic orchestration framework for intersections. This approach enables on-board vehicle intelligence and roadside signal control intelligence to reach an equilibrium solution through strategic interaction. Extensive evaluations demonstrate its superior performance in minimizing total travel time, validated across large-scale scenarios: 100 real-world intersections in Hangzhou and Jinan, and 1,089 simulated intersections in Manhattan.

2 Major results and findings

Addressing the challenges of exponential path explosion and the ultra-high-dimensional action space for millions of vehicles, we introduced large-scale vehicle-road collaborative path planning based on situational evolution. The comparative urban situational awareness and performance metrics are illustrated in Figure 2. Furthermore, Table 1 reveals quantitative results comparing the system's performance across two distinct urban environments.



(a) Beijing, China (b) Manhattan, New York, USA

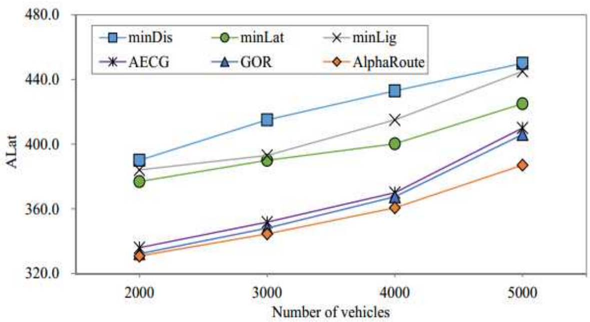


Figure 2 Urban situational awareness and performance comparations

Table 1 Performance on large-scale cities

Algorithm	Beijing Sub-district, Beijing				Upper East Side, Manhattan			
	Alat	Adis	AWai	ADet	Alat	Adis	AWai	ADet
minDis	450.91	6017.30	93.41	0.00	1009.56	1798.48	237.70	0.00
minLat	425.57	6114.80	79.99	97.50	894.32	1814.20	207.28	15.72
minLig	445.34	6023.12	94.23	12.01	994.23	1803.23	243.82	23.70
AECG	400.67	6134.21	65.76	178.21	751.23	1813.21	199.76	23.78
GOR	399.93	6151.97	56.94	134.67	744.60	1818.24	168.88	19.77
AlphaRoute	392.82	6115.13	50.83	97.83	692.53	1806.97	161.70	8.49

Research on 3D Perception Technologies Driven by Representation Decoupling

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Graphical abstract

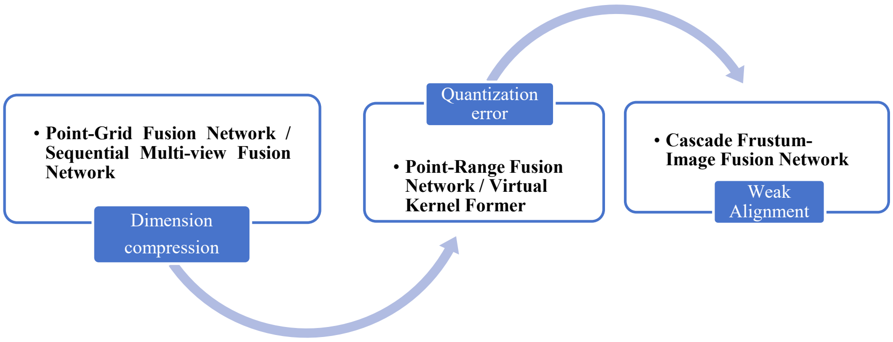

Figure 1 Graphical abstract

1 Objectives and Methodology

Autonomous driving perception serves as the critical foundation for safe navigation, providing environmental data to localization, planning, and sensing systems. Primary input modalities include LiDAR, cameras, and ultrasonic sensors. Point clouds—collections of 3D spatial points—characterize large-scale scenes with high precision. This irregular data structure typically employs three representations: raw points, voxels, or 2D projections. The point-based format preserves the richest information content as the most fundamental representation, yet presents three primary challenges: dimensionality reduction artifacts, quantization errors, and weak feature alignment. To address the aforementioned challenges, our work focuses on feature enhancement, multi-representation fusion, and feature alignment, proposing three corresponding solutions: 1) a Point-Grid / Sequential Multi-view Fusion Network, 2) a Point-Range Fusion Network with Virtual Kernel Former, and 3) a Cascade Frustum-Image Fusion Network.

2 Major results and findings

Point-based or sparse voxel-based methods are far away from real-time applications Recent 2D projection-based methods can run in realtime, but suffer from lower accuracy due to information loss during the 2D projection.

To achieve a better speed-accuracy trade-off, we propose Cascade Point-Grid Fusion Network (CPGNet), which ensures both effectiveness and efficiency mainly by the following two techniques: 1) the novel Point-Grid (PG) fusion block extracts semantic features mainly on the 2D projected grid for efficiency, while summarizes both 2D and 3D features on 3D points for minimal information loss; 2) the proposed transformation consistency loss narrows the gap between the single-time model inference and TTA.

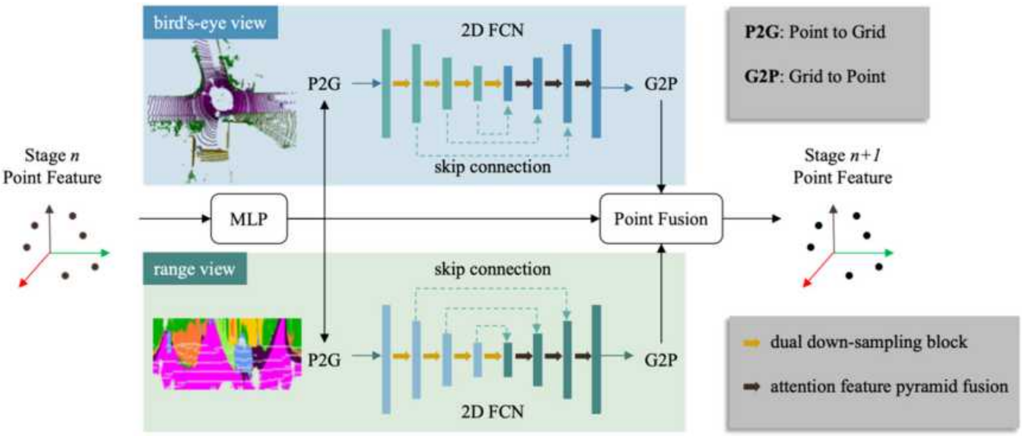

Figure 2 CPGNet pipeline

Table 1 CPGNet achieves the best speed-accuracy trade-off on the SemanticKITTI

Methods	**mIoU**	**speed (ms)**	Car	Bicycle	Motorcycle	Truck	Other-vehicle	Person	Bicyclist	Motorcyclist	Road	Parking	Sidewalk	Other-ground	Building	Fence	Vegetation	Trunk	Terrain	Pole	Traffic-sign
PointNet [1]	14.6	-	46.3	1.3	0.3	0.1	0.8	0.2	0.2	0.0	61.6	15.8	35.7	1.4	41.4	12.9	31.0	4.6	17.6	2.4	3.7
PointNet++ [2]	20.1	-	53.7	1.9	0.2	0.9	0.2	0.9	1.0	0.0	72.0	18.7	41.8	5.6	62.3	16.9	46.5	13.8	30.0	6.0	8.9
RandLA-Net [4]	53.9	521.8	94.2	26.0	25.8	40.1	38.9	49.2	48.2	7.2	90.7	60.3	73.7	20.4	86.9	56.3	81.4	61.3	66.8	49.2	47.7
KPConv [17]	58.8	-	96.0	30.2	42.5	33.4	44.3	61.5	61.6	11.8	88.8	61.3	72.7	31.6	90.5	64.2	84.8	69.2	69.1	56.4	47.4
RangeNet++ [14]	52.2	82.3	91.4	25.7	34.4	25.7	23.0	38.3	38.8	4.8	91.8	65.0	75.2	27.8	87.4	58.6	80.5	55.1	64.6	47.9	55.9
SqueezeSegv3 [25]	55.9	124.3	92.5	38.7	36.5	29.6	33.0	45.6	46.2	20.1	91.7	63.4	74.8	26.4	89.0	59.4	82.0	58.7	65.4	49.6	58.9
SalsaNext [26]	59.5	40.7	91.9	48.3	38.6	38.9	31.9	60.2	59.0	19.4	91.7	63.7	75.8	29.1	90.2	64.2	81.8	63.6	66.5	54.3	62.1
Lite-HDSeg [29]	63.8	-	92.3	40.0	55.4	37.7	39.6	59.2	71.6	54.1	93.0	68.2	78.3	29.3	91.5	65.0	78.2	65.8	65.1	59.5	67.7
MPF [15]	55.5	31	93.4	30.2	38.3	26.1	28.5	48.1	46.1	18.1	90.6	62.3	74.5	30.6	88.5	59.7	83.5	59.7	69.2	49.7	58.1
AMVNet [30]	65.3	-	96.2	59.9	54.2	48.8	45.7	71.0	65.7	11.0	90.1	71.0	75.8	32.4	92.4	69.1	85.6	71.7	69.6	62.7	67.2
SPVCNN [21]	63.8	187	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SPVNAS [21]	67.0	-	97.2	50.6	50.4	56.6	58.0	67.4	67.1	50.3	90.2	67.6	75.4	21.8	91.6	66.9	86.1	73.4	71.0	64.3	67.3
Cylinder3D [22]	67.8	178	97.1	67.6	64.0	59.0	58.6	73.9	67.9	36.0	91.4	65.1	75.5	32.3	91.0	66.5	85.4	71.8	68.5	62.6	65.6
DRINet [33]	67.5	62	96.9	57.0	56.0	43.3	54.5	69.4	75.1	58.9	90.7	65.0	75.2	26.2	91.5	67.3	85.2	72.6	68.8	63.5	66.0
AF2S3Net [23]	69.7	-	94.5	65.4	86.8	39.2	41.1	80.7	80.4	74.3	91.3	68.8	72.5	53.5	87.9	63.2	70.2	68.5	53.7	61.5	71.0
RPVNet [24]	70.3	168*	97.6	68.4	68.7	44.2	61.1	75.9	74.4	73.4	93.4	70.3	80.7	33.3	93.5	72.1	86.5	75.1	71.7	64.8	61.4
CPGNet [ours]	68.3	43/35.6*	96.7	62.9	61.1	56.7	55.3	72.1	73.9	27.9	92.9	68.0	78.1	24.6	92.7	71.1	84.6	72.9	70.2	64.5	71.9

Multi-Sensor Data Fusion Perception for Connected and Autonomous Vehicles

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Graphical abstract

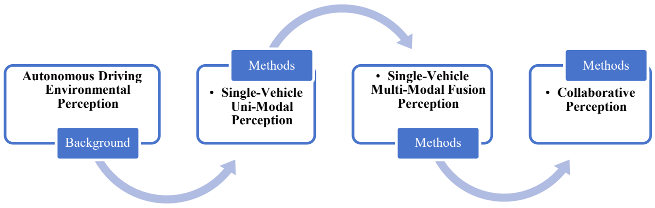

Figure 1 Graphical abstract

1 Objectives and Methodology

Vehicle control is undergoing a fundamental shift from mechanical systems to intelligent technologies. However, current single-vehicle intelligence still faces critical limitations: it struggles to ensure accurate perception beyond line-of-sight or under occlusion, and fails to maintain reliable sensing safety in adverse conditions like rain, snow, fog, or unexpected scenarios. To address the three major challenges in autonomous driving environmental perception—limited data diversity, poor target perception robustness, and constrained perception range of single-vehicle systems—we conduct dedicated research in Single-Vehicle Uni-Modal Perception, Single-Vehicle Multi-Modal Fusion Perception, and Collaborative Perception.

In the domain of single-vehicle intelligence, we proposed a Vision Self-Attention Feature Fusion Perception algorithm. This approach incorporates a multi-level visual self-attention feature fusion module and optimizes the object regression and classification loss functions, achieving robust perception results across diverse weather and lighting conditions. Furthermore, we developed a Vision-Radar Semantic Enhancement and Fusion Perception model. This model features a point cloud semantic enhancement module, introduces a point-wise feature fusion method, and integrates an IoU-aware branch, enabling highly efficient image-point cloud fusion perception.

In the domain of vehicular-edge intelligence, we introduced a Spatio-Temporal Feature Fusion and Cooperative Perception Framework for Multi-Vehicle Autonomous Driving. This framework includes the creation of a simulated multi-vehicle cooperative perception dataset, research on vehicle-to-vehicle (V2V) data fusion and cooperative perception architectures, and the proposal of an adaptive spatio-temporal feature fusion strategy for multi-vehicle systems. Furthermore, we developed a Dynamic Multi-Vehicle Multi-Modal Fusion and Cooperative Perception Algorithm. This work explores the fusion characteristics of single-vehicle and multi-vehicle data, incorporates a dynamic multi-sensor fusion module for individual vehicles, and designs a global-local Transformer co-network to enable collaborative reasoning.

Additionally, we established a Vehicle-Road-Aerial Multi-View Cooperative Perception Benchmark. This initiative curated a comprehensive autonomous driving perception dataset encompassing diverse maps, weather conditions (rain, snow, fog), and lighting scenarios from ground and aerial perspectives.

2 Major results and findings

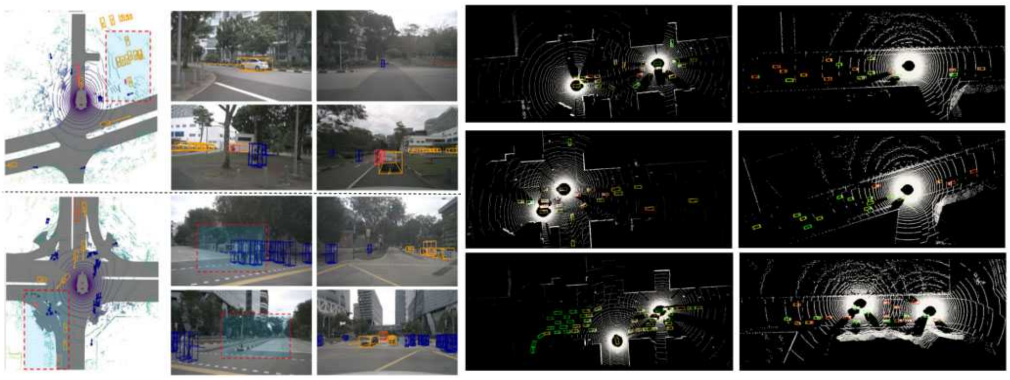

Figure 2 Performance of single-vehicle multi-modal fusion perception versus vehicle-to-vehicle vooperative multi-object perception

Table 1 Performance comparisons with other methods on OPV2V default/Culver City splits and V2X-SIM test set

Methods	**OPV2V** *Default*		**OPV2V** *Culver City*		**V2X-Sim** *Test*	
	AP@50 (%)	AP@70 (%)	AP@50 (%)	AP@70 (%)	AP@50 (%)	AP@70 (%)
V2VNet [14]	82.2	79.4	73.4	68.9	56.8	50.7
DiscoNet [50]	80.1	76.8	75.0	70.3	*60.3*	*53.9*
OPV2V-attn [23]	86.4	80.2	77.5	73.6	59.4	53.3
CoBEVT [59]	86.1	81.6	77.3	73.1	-	-
FPV-RCNN [61]	82.0	77.3	76.3	72.0	-	-
Where2comm [62]	88.9	75.5	82.2	68.0	59.1	52.2
CORE [52]	*90.9*	*85.8*	*87.7*	*78.1*	-	-
SECOND-*CoTr*	**91.7** (+0.8)	**87.6** (+1.8)	**89.3** (+1.6)	**80.5** (+2.4)	**61.5** (+1.2)	**55.0** (+1.1)

Paralel Session E1

Topic: Intelligent Pavement Condition Inspection & Maintenance

Chair: You Zhan, Associate Professor, Southwest Jiaotong University
Cochair: Aonan Zhang, Professor, Southwest Jiaotong University

Introduction:

The rapid development of highway networks and the increasing demand for service quality have posed new challenges for pavement inspection and maintenance. Traditional methods, relying heavily on manual interpretation and empirical strategies, often struggle with efficiency, accuracy, and adaptability under complex traffic and environmental conditions. Recent advances in artificial intelligence, sensing technologies, and materials science are revolutionizing pavement engineering, enabling intelligent and automated solutions for condition assessment, performance prediction, and maintenance decision-making.

This conference brings together five cutting-edge studies that reflect the multi-dimensional progress in this domain. From the perspective of data-driven decision-making, new frameworks integrating empirical knowledge with machine learning, BiLSTM prediction models, and reinforcement learning–based maintenance strategies are proposed, offering systematic "evaluation–prediction–decision" pipelines for pavement management. In the field of subsurface defect and pipeline detection, novel approaches leveraging feature fusion, attention mechanisms, and optimized deep learning architectures significantly improve the robustness of GPR image interpretation, addressing long-standing challenges of noise interference and small-target recognition.

On the material innovation front, research into stress-controlled release calcium alginate capsules introduces a promising pathway for self-healing asphalt, capable of automatically releasing rejuvenating agents under vehicle load to restore aged asphalt and heal microcracks. This represents a fundamental shift from reactive maintenance to proactive material-level regeneration. Meanwhile, advancements in high-precision, real-time pavement distress detection highlight the potential of 3D laser imaging systems coupled with intelligent recognition algorithms such as ShuttleNet, achieving millimeter-level accuracy and supporting full-process automated inspection at highway speeds. Complementing these, comparative studies on anchor-free vision transformers for pavement distress detection systematically evaluate trade-offs between one-stage and two-stage object detectors, as well as anchor-based and anchor-free paradigms, revealing optimal strategies to balance accuracy, computational efficiency, and adaptability across complex road environments.

Together, these contributions demonstrate that intelligent pavement condition inspection and maintenance is evolving into a comprehensive discipline integrating sensing, deep learning, decision science, and smart materials. They collectively pave the way toward predictive, efficient, and sustainable pavement management systems, offering strong technical support for the construction of intelligent transportation infrastructure.

Speech:

Intelligent Computational Methods for Pavement Performance Evaluation and Maintenance Decision-Making

You Zhan, Southwest Jiaotong University

Intelligent Recognition of GPR Road Hidden Defect and Pipeline Images Based on Feature Fusion and Attention Mechanism

Zepeng Fan, Harbin Institute of Technology

Stress Controlled Release Capsules for Asphalt Self-healing

Quantao Liu, Wuhan University of Technology

High-Precision Real-Time Intelligent Detection of Pavement Distresses

Aonan Zhang, Southwest Jiaotong University

Automated Pavement Distress Detection using an Anchor-free Vision Transformer

Hongren Gong, Tongji University

Intelligent Computational Methods for Pavement Performance Evaluation and Maintenance Decision-Making

You Zhan
Southwest Jiaotong University

Abstract

During prolonged operational service, highway pavements undergo continuous traffic loading, leading to progressive deterioration of their service performance under the combined action of external environmental factors. To ensure the service function and safety of the highway, it is imperative to establish a scientifically sound pavement performance evaluation methodology, achieve accurate prediction of performance evolution trends, and develop effective maintenance strategies. This study focuses on the Sichuan highway as the research subject, conducting comprehensive investigations into its typical disease characteristics, climatic conditions, traffic conditions, historical performance inspection data, and maintenance records. The research develops three interconnected models: a pavement performance evaluation model that integrates empirical knowledge with machine learning algorithms, a BiLSTM-based pavement performance prediction model, and a Dueling DQN maintenance decision-making model that synthetically incorporates both evaluation and prediction outcomes. Through systematic study of combined subjective-objective evaluation approaches, neural networks, and reinforcement learning applications in highway pavement performance evaluation, prediction, and maintenance decision-making, this study establishes an intelligent highway pavement management system featuring an integrated "evaluation-prediction-maintenance" paradigm. Firstly, the study discusses fundamental characteristics of Sichuan highways, including pavement structures, climatic conditions, traffic conditions, and inspection data, analyzing typical disease characteristics and their causative mechanisms across five selected highways. By integrating disease characteristics with performance indicators and maintenance thresholds, domain knowledge is formalized as knowledge functions. These functions are incorporated into the loss function of an XGBoost model, with hyperparameter optimization conducted using the SSA algorithm to maximize evaluation accuracy. Results demonstrate 98% consistency between the model's PQI grade and the evaluation grade of "Highway Technical Condition Evaluation Standard", with the evaluation results showing better alignment with actual road conditions at the boundary between "excellent" and "good" grades. Secondly, utilizing 2019-2022 inspection data from five Sichuan highways, time-series datasets incorporating pavement structure, climate, and traffic volume are established. The BiLSTM algorithm is employed to develop separate prediction models for PCI, RQI, RDI, PBI and PWI indices. The prediction performance of the BiLSTM model is compared with that of the LSTM baseline model, and the SHAP model is used to analyze the influence of each input parameter on the output results. The results show that the BiLSTM model performs better. After hyperparameter tuning, the R^2 value of each prediction model exceeds 0.8. Road age and traffic volume are the main factors affecting pavement performance. Finally, a Dueling DQN maintenance decision-making model is constructed based on the BiLSTM prediction model and the pavement performance evaluation model to

assess dynamic pavement state, with the goal of maximizing the long-term comprehensive benefit-cost ratio through "trial and error-feedback" learning. The model's performance is compared with the DQN baseline model. The better maintenance decision-making model is applied to develop a 10-year maintenance decision for the Chengdu-Chongqing Highway. The study shows that the Dueling DQN model has faster convergence speed and smaller fluctuation. The maintenance strategy for the Chengdu-Chongqing Highway prioritizes routine maintenance and preventive maintenance, with thin-layer overlay being the most commonly used measure. Both the length of maintenance and maintenance costs show cyclical variations.
Keywords: Pavement service performance, Knowledge fusion, Pavement performance prediction, Reinforcement learning, Maintenance decision-making

Intelligent Recognition of GPR Road Hidden Defect and Pipeline Images Based on Feature Fusion and Attention Mechanism

Zepeng Fan
Harbin Institute of Technology

Abstract

Manual interpretation in ground-penetrating radar (GPR) surveys often suffers from low efficiency, limited capability in detecting small targets under complex conditions, and insufficient robustness. To overcome these challenges, this study presents an intelligent recognition framework for concealed pavement distresses and underground pipelines by integrating deep learning optimization strategies. A DCGAN-based data augmentation method is employed to mitigate sample scarcity, while two specialized models are proposed: MCGA-Net, which combines Multi-modal Chain Feature Fusion (MCFF) with a Global Attention Mechanism (GAM) to strengthen multi-scale defect representation, and DCO-YOLO, which incorporates Dynamic Oversampling (DySample), Outlook Attention, and a 3D Spatial Feature Matching algorithm (3D-DIoU) to improve pipeline edge feature extraction and multi-view association accuracy. Furthermore, transfer learning and physical feature constraints are integrated to enhance generalization. Experimental results demonstrate that the proposed models achieve superior performance in subsurface defect and pipeline detection, exhibiting strong robustness against noise interference, weak signals, and complex multi-target scenarios. This work provides an efficient and accurate technical framework for automated subsurface detection.

Keywords: Ground-penetrating radar (GPR); Subsurface defect detection; Underground pipeline recognition; Deep learning; Feature fusion; Attention mechanism; Robust detection

Stress Controlled Release Capsules for Asphalt Self-healing

Quantao Liu
Wuhan University of Technology

Abstract

Using the self-healing property of asphalt concrete to close micro cracks in asphalt pavement has become an advanced pavement cracking maintenance concept at home and abroad, but no practical self-healing method has been developed so far. In previous research, the author found that multi-cavity calcium alginate capsules have stress-controlled release characteristics and can automatically release the healing agent inside of the cavities due to elastic shrinkage under vehicle load. If the healing agent release speed can be ensured to match the aging and damage degree of asphalt pavement, in-situ regeneration of aged asphalt and automatic healing of microcracks will be realized. In order to design the stress-controlled release type multi-cavity self-healing capsules with a release speed matching the aging and damage degree of asphalt pavement, and to solve the aging and cracking problem of asphalt pavement from the source, the author carried out in-depth research on the preparation method, the release speed and regulation of healing agent, the regeneration and healing effect, and the action mechanism of calcium alginate multi-cavity capsules. The optimal preparation parameters and wall material reinforcement method of multi-cavity calcium alginate asphalt self-healing capsules were put forward. The healing agent content of the capsules prepared can reach 76%, and it will not break after being mixed into asphalt mixture and compacted, and the healing agent release rate is less than 5% after compaction. The relationship between the microstructure and compression performance of the capsule and its stress-controlled release characteristics was clarified, and the stress-controlled release type multi-chamber calcium alginate capsules with release rate matching the aging and damage degree of asphalt pavement were prepared to ensure that the capsules in asphalt pavement release 55.2%a and 82.67% of the healing agent after servicing for 4 and 7 years respectively. The in-situ regeneration effect on the aged asphalt and the healing efficiency of microcracks of the capsules after the release of repair agent were explored, and the action mechanism of the stress-controlled release multi-cavity calcium alginate capsules was revealed. The fracture strength recovery rate of asphalt concrete reached 92.7%, and the fracture energy recovery rate reached 180.2%, and the long-term aged asphalt was effectively regenerated. The rapid preparation technology of multi-chamber self-healing capsules was developed by using industrial grade raw materials and industrial equipment, and the preparation efficiency was improved by more than 200 times, laying a scientific foundation for its practical application. The output of this project will help to solve the aging and cracking problems of asphalt pavement from the source, which has great economic, social and environmental benefits.

Keywords: Asphalt; Calcium alginate capsules; Stress controlled release; Self-healing; Rejuvenation

High-Precision Real-Time Intelligent Detection of Pavement Distresses

Aonan Zhang
Southwest Jiaotong University

Abstract

The advancement of intelligent pavement condition survey faces a core challenge in achieving coordinated improvements in accuracy, functionality, and timeliness. To address this, this paper established a real-time intelligent pavement condition survey framework based on a 3D laser imaging system, and achieved key breakthroughs in high-precision 3D laser imaging, massive 3D data compression and storage, and real-time intelligent recognition algorithms for multi-target identification including pavement distresses and surface design features.

The 3D laser imaging system was capable of acquiring high-precision 2D and 3D pavement data in real time at a speed of 120 km/h, which provided robust data support for intelligent recognition and refined assessment. Operating on a road inspection vehicle, the system uses a laser emitter and 3D cameras (functioning as 2D cameras simultaneously) arranged in a triangular geometry to acquire reflected laser signals, generating continuous pavement image data. Equipped with left and right camera groups (each containing two 3D cameras), the system covers a 4-meter-wide pavement section, triggered by a Distance Measurement Instrument (DMI) to alternate camera activation. This design achieves 1 mm lateral and longitudinal resolution, a scanning rate of 30 kHz (30,000 lines of 3D data per second), and a height measurement error below 1%, even at speeds up to 120 km/h. While ensuring data quality, the massive 3D data compression and storage algorithm (Fast Point Cloud Aggregation) significantly reduced storage and transmission demands, enhanced memory efficiency, and ensured stable data acquisition during continuous high-speed operation.

The proposed multi-target real-time intelligent recognition algorithm(ShuttleNet) achieved pixel-level accuracy in identifying various pavement objects including pavement background, crack, pothole, sealed crack, patch, scratch, marking, manhole, expansion joints, and concrete slab joints. The core innovation of the ShuttleNet model lies in its repeated utilization of the "encoder-decoder" architecture, constructing successive "encoder-decoder" cycles. Within each "encoder-decoder" cycle, the model performs operations such as 3×3 convolution, Batch Normalization (BN), the ReLU nonlinear activation function, feature concatenation (Concat), and Memory Connection. These operations enable the model to deeply explore the latent representations of pavement distresses while maintaining the original spatial dimensions. During each "encoder-decoder" cycle, feature information is encoded at different resolutions, progressively extracting high-level abstract semantic information. To meet the requirements of real-time intelligent processing, this paper proposes a speed optimization method (model pruning and model quantization) for the ShuttleNet model. This method aims to achieve fast inference while maintaining high accuracy. After model pruning and quantization, the model achieved an inference speed of 6 ms per frame. Field verification demonstrated that the integrated processing speed of the proposed high-precision and real-time intelligent pavement condition survey system reached 160 km/h, and that it was capable of completing full-process operations including data collection, intelligent analysis, and report generation for 400 km of road pavement within a single day.

On the 6,000-image test dataset, ShuttleNet outperformed other mainstream models across multiple key metrics for road pavement distress recognition. ShuttleNet achieved a mean Recall of 92.82%, higher than U-Net (90.09%), DeepLabv3+ (ResNet-101) (93.27%), HRNet-OCR (HRNetV2-W48) (90.59%), and SegFormer-B5 (89.64%). This indicates that ShuttleNet can more comprehensively recall features of various distress types and reduce the possibility of missed detections when identifying road pavement distresses. Simultaneously, ShuttleNet also achieved the highest mean Precision score, demonstrating its excellent accuracy in recognition results and its effectiveness in avoiding false detections. Combining these two metrics, ShuttleNet's mean F1-Score reached 94.34%, the highest among all models, further highlighting its advantage in recognition accuracy. Furthermore, ShuttleNet's mean IoU of 90.68% was also higher than other models, signifying its distinct advantage in the accuracy of segmenting target areas on the road surface, enabling more precise localization and delineation of pavement target regions.

The results show that the proposed framework meets both high-precision and high-efficiency requirements, and exhibits strong robustness in recognizing complex pavement distresses. This paper provides an efficient and feasible technical reference for comprehensive, accurate, and timely assessment of pavement conditions, thereby supporting preventive maintenance strategies for pavement management systems.

Keywords：Road engineering; Intelligent pavement condition survey; Deep learning; Pavement distresses; Pavement cracks; 3D data compression; 3D laser imaging system

Automated Pavement Distress Detection using an Anchor-free Vision Transformer

Hongren Gong
Tongji University

Abstract

This study investigates key architectural trade-offs in modern object detection systems, comparing one-stage (YOLO, SSD, DETR) and two-stage (Faster R-CNN) detectors, alongside anchor-based (Faster R-CNN, YOLOv5) and anchor-free (FCOS, YOLOv10, DINO) paradigms for pavement surface defects detection. Analysis reveals two-stage detectors offer higher accuracy, particularly for small objects and better localization via iterative refinement, but incur significant computational overhead and complexity, limiting real-time use. Conversely, one-stage detectors provide faster inference through simpler end-to-end designs but face challenges with accuracy in complex scenes and extreme class imbalance. Anchor-based methods rely on predefined boxes, easing training and boosting recall for standard objects yet introducing inflexibility and hyperparameter sensitivity. Anchor-free approaches eliminate anchor constraints, enhancing flexibility for irregular shapes and simplifying architectures, but can suffer from complex keypoints grouping and convergence instability. Comprehensive experiments evaluate 20 model variants (including DINO, Faster R-CNN, and YOLO families with Swin Transformer, ResNet, and Darknet backbones) across multiple training scales. Rigorous multi-scale testing protocols and metrics (mAP, mAR, F1-score) demonstrate that optimal detector selection hinges on balancing accuracy, speed, flexibility, and computational resources, with architecture, backbone choice, and evaluation strategy critically impacting performance.

Keywords：Pavement distress detection; Vision Transformer; Anchor-free detection; One-stage detector; Two-stage detector; Deep learning; Object detection

Parallel Session E2

Topic: Pavement Skid Resistance Monitoring and Enhancement Technologies

Chair: Dawei Wang, Professor, Harbin Institute ofTechnology
Cochair: Hongzhou Zhu, Professor, Chongqing Jiaotong University

Introduction:

Skid resistance is a critical indicator of road safety, directly influencing vehicle stability, braking performance, and maneuverability under wet or extreme weather conditions. With the rapid development of intelligent transportation systems and the increasing frequency of climate-induced hazards, the monitoring, evaluation, and long-term preservation of pavement friction are facing new technical challenges. Achieving high-precision characterization, predictive modeling, and intelligent intervention mechanisms for skid resistance has become a key focus in modern pavement engineering.

The TRC sub-forum "Pavement Skid Resistance Monitoring and Enhancement Technologies" brings together renowned experts including Prof. Xinglin Zhou and Assoc. Prof. Maoping Ran, Prof. Lingyun Kong, Assoc. Prof. Zhi Li (South China University of Technology), Prof. Eng. Tao Wen, and Assoc. Prof. You Zhan. These scholars will deliver invited talks and engage in in-depth discussions on the most prominent and promising areas of research.

The forum will focus on cutting-edge topics such as 3D texture reconstruction for realistic digital representation of pavement surfaces; super-resolution modeling techniques for enhancing low-resolution texture data across scales; microstructural analysis of asphalt materials to uncover the intrinsic mechanisms influencing friction performance; and long-term predictive modeling of skid resistance evolution to support performance-based maintenance and design strategies. By integrating experimental technologies with data-driven approaches, the forum will explore comprehensive and intelligent solutions for pavement friction monitoring and enhancement. This session aims to promote interdisciplinary collaboration across materials science, sensing technology, and transportation engineering. It will help establish a complete technical chain from surface characterization to performance prediction, contributing to the development of smart, resilient, and high-performance pavement infrastructure for highways, urban roads, and airport runways.

Speech:

Macroscopic Analysis of the Contributions of Asphalt and Aggregates to Pavement Skid Resistance

Lingyun Kong, Chongqing Jiaotong University

Investigation ofPavement Skid Resistance Contact Characteristics Using Pressure-Sensitive Film Technology

Zhi Li, Associate, China University ofTechnology

Key Technologies forPavement Icing Monitoring, Early Warning, and ProactiveResponse Assurance

Tao Wen, RInstitute of Highway Ministry of Transport

Research and Application Development of High-Precision 3D Pavement Texture Super-Resolution Reconstruction and Skid Resistance Evaluation Methods

You Zhan, Southwest Jiaotong University

Macroscopic Analysis of the Contributions of Asphalt and Aggregates to Pavement Skid Resistance

Lingyun Kong
Chongqing Jiaotong University

孔教授的报告聚焦于高速公路，特别是隧道在竣工验收环节普遍存在的路面抗滑性能不达标问题，以及路面抗滑耐久性不足的工程痛点，提出了一套从材料源头优选、功能性外加剂创新到施工工艺精细化控制的系统性、实效性解决方案。其研究，旨在解决常规集料在长期服役中抗磨光能力差、隧道特殊运营环境下油膜污染导致路面湿滑，以及标准施工流程未能充分发挥材料性能潜力等一系列紧迫的工程难题，为建设更高质量、更安全的耐久性路面提供了经过实践检验的宝贵经验和技术指导。

在材料基础研究与选材方面，孔教授通过现场观察与室内加速加载试验，深刻揭示了集料的"基因"——即其内在的物理化学特性，对路面长期抗滑性能具有决定性影响。为量化这一影响，孔教授团队开展的对比试验包括：在级配、沥青完全相同的条件下，使用加速加载设备对采用常规玄武岩和重庆地区特有的一种石英细砂岩的沥青混合料，分别进行了 150 万次荷载的模拟测试。试验结果表现出显著差异：采用玄武岩的路面，其 BPN 值（英国摆锤值）衰减了约 15%；而采用石英细砂岩的路面，其 BPN 值则几乎没有衰减，展现出极强的抗磨光能力。这一结果有力地证明，集料自身的化学成分和微观结构是其抵抗荷载抛光效应的根本，从源头上选择具有优异抗磨光性能的"基因"材料，是保障路面抗滑性能长效稳定的首要前提。

针对隧道这一抗滑性能的"重灾区"，孔教授团队深入剖析了其性能偏低的根本原因，并为此开创性地研发了一种功能性沥青外加剂。研究发现，隧道作为相对密闭的空间，车辆尾气（尤其是在燃烧不充分时）不易扩散，其中的油性颗粒物会大量沉积于路面，日积月累形成一层危险的黑色油膜，导致路面极度湿滑（现场用手触摸会沾染一层油污），这也是隧道竣工时抗滑系数普遍低于洞外路段（如洞外 47-48，洞内仅 41-42 甚至更低）的核心原因。为解决此难题，孔教授团队研发了一种"沥青耐污剂"。该助剂通过改变沥青的表面能，使其呈现出"亲水疏油"的特性，具体表现为水接触角大幅减小（由约 100 度降至 10 度），油接触角大幅增大（由约 30 度升至 50 度）。这一特性旨在实现两大功能：一、让油污难以在路面牢固粘附（"粘不住"）；二、让已经附着的油污在雨水或简单冲洗下极易被清除（"好清洗"）。通过室内模拟尾气污染和水枪冲洗的试验验证，添加该耐污剂的沥青试件在冲洗后，其摩擦系数恢复效果和油污残留量均远优于普通沥青试件，为根治隧道油膜污染问题提供了有效的材料学解决方案。

为解决即使采用合格材料，路面初始抗滑性能仍可能不达标的问题，孔教授团队从施工工艺环节入手，提出并验证了一项"零成本"的优化措施。在许多 SMA（沥青玛蹄脂碎石）路面施工中，为防止富含沥青的玛蹄脂上浮（提浆），施工单位通常仅使用钢轮压路机进行碾压，但这可能导致路表构造未能充分形成。针对此情况，研究团队在一个隧道 SMA 路面项目中进行了工艺改进试验，在标准的初压、复压（钢轮）工序完成后，增加了两遍胶轮压路机的终压环节。此举的关键在于，胶轮碾压是在混合料已具备一定稳定性的阶段进行，其揉搓作用能有效调整表面集料的朝向，形成更优良的宏观纹理，而不会导致提浆现象。现场实测结果发现：这一简单的工艺调整，使得路面的初始 BPN 值直接增加了 2 个点，这在验收中往往是合格与否的关键，有效避免了路面"输在起跑线上"。

孔教授团队的系列成果形成了一套覆盖材料、外加剂和施工工艺的完整技术体系，为高速公路特别是隧道等关键路段的抗滑性能保障提供了极具工程应用价值的综合解决方案。研究成果不仅从理论上揭示了抗滑性能衰减的深层原因，更重要的是提供了经过实践验证、经济可行的具体措施。这些技术已在广东某隧道的试验段中得到初步应用，其成果对于指导未来道路的设计、施工与竣工验收，从全流程提升道路的初始及长期安全水平具有重大的现实意义和推广价值。

Investigation ofPavement Skid Resistance Contact Characteristics Using Pressure-Sensitive Film Technology

Zhi Li,Associate
China University ofTechnology

李智教授指出了目前路面抗滑性能传统认知与研究范式面临的挑战，李智教授在本次报告中介绍了其团队提出的一套以“接触力学”为核心的全新理论框架与实验方法。李智教授团队指出，将复杂的抗滑问题简单归结为测量单一的“摩擦”系数是远远不够的，其物理本质在于轮胎与路面之间在动态、多尺度条件下的“接触”与“相互作用”。当前标准化的检测手段与数值模型，往往将路面简化为一个具有特定摩擦系数的平面，这忽略了接触区域内极为复杂的应力分布、橡胶变形以及集料颗粒的力学互锁机制。李智教授团队通过引入一种创新的可视化检测技术，致力于解决传统方法无法直接测量接触界面参数、难以反映真实接触状态的根本性问题，旨在为路面功能性设计、耐久性评估及机理模型构建提供更科学、更深入的理论基础与实测依据。

首先，在理论框架重构方面，李智教授团队提出“接触才是本质问题，摩擦只是接触中的一部分”的核心理念，发现路面抗滑性能源于轮胎橡胶与路面多尺度纹理之间复杂的力学与物理化学相互作用，这一过程受到路面（材料、构造、耐久性）和轮胎（橡胶弹性、胎压、花纹）双方特性的共同影响。轮胎花纹不仅用于排水，其凹槽和边缘更是为了与路面的宏观和微观凸起形成有效的机械“咬合”。因此，总的抗滑力是粘滞力（源于分子间作用）、迟滞力（源于橡胶变形恢复的能量损失）以及由这种机械互锁产生的“咬合效应”的综合体现。李智教授在报告中强调，对于路面抗滑性能的耐久性而言，当集料表面在长期行车荷载下逐渐被磨光后，由级配和颗粒形态决定的咬合效应，将成为维持基本安全水平的决定性因素。这一理论框架成功地将研究焦点从一个宏观、经验性的摩擦力测量，转向了对接触界面力学行为的微观、机理性探究。

其次，为给上述理论框架提供实验支撑，李智教授团队引入了“压力感应胶片”这一核心检测技术，以实现对轮胎-路面接触界面的直接、高精度可视化测量。该技术基于物理化学原理，胶片内部含有显色剂微胶囊，当受到压力时，胶囊破裂并与显色层发生反应，形成颜色深浅与压力大小成正比的红色印记。通过高精度扫描仪将反应后的胶片数字化，便可获得接触区域内详尽的二维压力分布云图。利用该技术进行的一系列室内试验，直观地揭示了轮胎与真实沥青路面（如 SMA、AC 等）的接触真相：接触并非一个均匀承压的面，而是由少数粗集料的顶端承受了绝大部分荷载，呈现为一系列离散、高应力的“点接触”形态。这一发现颠覆了许多传统模型中均布荷载的假设，并允许研究人员首次定量计算有效接触面积、压力峰值、应力梯度等一系列全新的评价指标，从而对接触的“质量”进行前所未有的深入评估。

李智教授团队利用压力感应胶片技术，针对轮胎与路面纹理的“咬合效应”开展研究。为模拟和量化轮胎橡胶嵌入集料间隙的力学行为，团队设计了独特的试验方法，例如使用单一粒径的钢珠阵列来模拟理想化的路面构造，并让轮胎以低速碾压。通过测量压力分布和分析钢珠位移，该试验能够反演出轮胎橡胶的变形和嵌入深度，从而隔离并研究咬合机制。基于这些试验，团队引入了“咬合深度”和“咬合面积”等创新参数来表征咬合效应的强度。通过对不同粒径组合的分析，研究得出了一个极为重要的结论：粒径或凸起尺寸在 7 至 9 毫米范围内的集料构造，能够与轮胎形成最佳的咬合关系，从而最有效地产生抵抗滑动的水平制动力。

这一发现为优化路面表面层的集料级配、设计即使在磨光后仍能保持较高抗滑性能的耐久性路面，提供了明确的科学依据，并对现有评价指标能否有效表征此效应提出了深刻的思考。

最后，李智教授团队通过构建新的理论框架和引入创新的检测手段，为路面抗滑性能研究开辟了新的路径，实现了从宏观“摩擦”研究到微观“接触力学”研究的范式转变。团队不仅在理论上强调了接触相互作用的本质地位，更通过压力感应胶片技术将这一理念付诸实践，实现了对轮胎-路面相互作用前所未有的深入洞察。研究成果对于改进路面功能性设计、完善抗滑性能评价方法以及开发更逼真的数值仿真模型均具有重要的指导价值。李智教授建议，将该技术与现有的环道加速加载设备相结合，并利用其获取的真实接触数据来标定和验证更先进的力学模型，可推动路面工程向更精细、更科学化的方向发展。

Key Technologies for Pavement Icing Monitoring, Early Warning, and Proactive Response Assurance

Tao Wen

Research Institute of Highway Ministry of Transport

文涛博士针对路面结冰及湿滑对交通安全的严重威胁，在报告中提出了一套集“精准监测、智能预警、主动处置”于一体的综合性智慧交通气象保障技术体系。其指出，由冰、雪等恶劣天气引发的交通安全问题极为突出，其中，路面结冰，尤其是因其透明、难以被肉眼察觉而被称为“隐形杀手”的“黑冰”，是导致冬季车辆失控、引发重特大交通事故的主要元凶之一。针对当前道路气象监测网络覆盖密度不足、预警信息时空精度不高、传统融雪除冰作业主要依赖人工经验、效率和环保性均有欠缺等行业痛点，文涛博士团队通过研发一系列关键传感器、预测模型和自动化装备，实现对道路结冰风险的全要素感知、全时空预警和全天候自动化干预，从而显著提升道路在极端天气下的安全韧性和通行保障能力。

首先，在核心的监测感知技术方面，文涛博士团队围绕“测得准、测得全”的目标取得了一系列关键突破。为解决“黑冰”的探测难题，成功研发了一种先进的非接触式路面状态传感器。该传感器创新性地采用了三个特定波长的光谱对路面进行探测，通过深度分析不同路面状态（包括干燥、潮湿、积水、普通结冰、黑冰）下独特的反射光谱特征，并构建高精度的判别算法模型，最终实现了对“黑冰”超过 90%的准确识别，解决了该领域长期存在的技术瓶颈。为弥补高速公路沿线固定气象站（平均间距可达 50 公里）空间覆盖不足的短板，研究还开发了一款即插即用的“车载式移动交通气象站”。该设备可便捷地安装于日常养护巡逻车上，在车辆行驶过程中连续采集并回传沿线的路面温度、空气温湿度等关键数据，从而获取了固定站点之间路段状态的动态、高密度信息，为构建空间连续的温度场预测模型提供了不可或缺的数据基础。

其次，基于多源、精准的监测数据，文涛博士团队构建了时空一体化的路面状态精细化预测预警模型。该模型体系的关键创新在于，它不仅能实现单个站点的未来时间序列预测，更能完成整条路段在空间维度上的精准预测。通过融合车载移动气象站采集的空间数据和固定气象站采集的时间数据，建立了特定路段在不同气象背景下的空间温度分布规律模型。系统能够基于此模型，结合最新的气象预报，生成未来特定时间点沿线每 500 米甚至更短距离的路面温度分布图。在此基础上，进一步建立了路面结冰预警规则模型，该模型综合考虑了路面预测温度、空气湿度、露点温度以及降水相态等多个因素，能够以极高的时空精度，预测出未来特定时间段内，在哪一个具体桩号位置，发生结冰的可能性有多大，以及可能的结冰类型。这种“定时、定点、定量”的预警能力，是实现后续主动、精准、高效处置的决策核心。

再者，该系统的最大亮点在于将先进的监测预警技术与自动化处置装备相结合，开发并成功应用了“主动式智能融雪除冰系统”，实现了从传统的被动“除冰”到先进的主动“防冰”的理念跨越。该系统是一套集成了感知、决策和执行的闭环自动化系统，主要部署在桥梁、隧道出入口、匝道、长下坡等公认的易结冰高风险路段。一旦系统接收到前端监测网络和后端预测模型发出的高风险结冰预警指令，其便会在路面结冰形成之前，通过预埋在路侧或中央分隔带的管道和特制喷头，自动向路面喷洒环保型融雪溶液。该系统的核心技术不仅在于硬件设备，更在于其智能化的喷洒控制策略。该策略能够综合考虑天气类型、预期降温速率、路面坡度、交通流量等多种因素，精确控制喷洒的启动时间、持续时长、溶液用

量以及喷洒模式（如仅喷洒关键的轮迹带），从而在确保路面不结冰的前提下，最大限度地节约融雪剂并减少对环境的潜在影响。

最后，文涛博士团队系列成果已成功集成为一套完整的智慧交通气象保障系统，并在北京、新疆等地的实际工程中得到部署应用和持续验证，取得了良好的效果。该系统通过创新的多源监测手段、精准的时空预测模型和智能化的主动处置装备，形成了一套完整的技术闭环，有效解决了冬季道路结冰湿滑的核心安全难题。相关技术成果经行业权威专家鉴定，在路面温度连续辨识与结冰监测技术方面达到国际领先水平，并获得了多项省部级科技奖励。这项研究不仅为道路运营管理部门提供了强大的技术工具，也为国家交通气象保障网络规划的落地实施提供了重要的技术支撑，对于提升我国公路网在极端天气下的安全韧性和通行效率具有深远的战略意义和广泛的应用前景。

Research and Application Development of High-Precision 3D Pavement Texture Super-Resolution Reconstruction and Skid Resistance Evaluation Methods

You Zhan
Southwest Jiaotong University

战友副教授针对路面抗滑性能非接触式评估中高精度三维纹理数据连续采集与抗滑预测的关键问题，提出了一种基于深度学习和机器学习的综合解决方案。通过构建超分辨率网络实现路面三维纹理的 0.1mm 高精度重构，并融合超参数寻优算法和机器学习模型，构建了高效的抗滑性能预测方法。战友副教授的研究旨在解决传统接触式测量效率低下、车载激光扫描设备采集分辨率不足、现有抗滑评价模型泛化性能有限等问题。

首先，在数据支撑方面，通过室内加速加载磨耗试验，并利用 LS-40 激光扫描仪和摆式摩擦仪测量了不同磨耗阶段的纹理数据及对应的英国摆锤值 BPN，构建了包含 528 组高精度三维纹理与抗滑性能配对的标准化样本库。通过数据归一化和子样本分割技术，将训练集扩充至 3789 组，有效解决样本稀缺性问题。通过构建纹理维度保持机制，确保二维图像域重构结果可准确恢复至包含高程信息的三维点云。

其次，设计了基于循环递归超分辨率网络的三维纹理重构模型。该模型融合拉普拉斯金字塔池和递归架构，结合异步步长上采样设计，实现了行车方向上路面纹理的多级重构。设计两阶段训练策略，并基于残差连接模块和批归一化模块设置两组消融试验。结合残差模块和批归一化的模型在测试集表现出最优性能：所有重构倍率下的 PSNR 均大于 30dB，SSIM 均高于 0.9，平均纹理深度（MTD）的平均相对误差绝对值低于 1.36%，显著优于传统双三次插值法。此外，超分辨率模型最高支持 8 倍动态重构，理论上可在 128km/h 车速下实现 0.1mm 精度的路面三维纹理采集。

为实现路面超分辨率重构纹理的抗滑性能非接触式预测，提出了鱼鹰优化算法（Osprey Otimazation Algorithm，OOA）和机器学习的融合模型。通过提取路面宏微观纹理的几何统计特征、分形维数，结合磨耗次数等动态参数，构建了多维度特征体系。利用 OOA 寻找随机森林（RF）、XGBoost、LightGBM 模型的最佳超参数。其中，OOA-RF 模型的预测结果最稳健，实现各级超分辨率重构纹理下，其抗滑预测 R^2 均大于 0.8。基于沙普利加和解释法（Shapley Additiveex Planations，SHAP）的特征重要性分析表明，磨耗次数、MTD 和分形维数对抗滑性能影响显著。基于 SHAP 的特征简化研究表明，微观纹理特征对抗滑性能的贡献不可忽略。

最后，基于 PyQt6 和 MySQL 开发了集成化软件系统，实现了从纹理高精度重构到抗滑预测的全流程自动化评估。黑盒测试结果表明，开发的软件能够稳定运行所设计的功能，对交通基础设施养护具有重要应用价值。

综上所述，各位专家从机理认知、智能监测到工程实践，系统阐述了路面抗滑性能保障的技术进展，凸显了多学科交叉融合的重要发展趋势

Paralel Session F1

Topic: New Technologies in Cement Concrete Pavement

Chair: Ya Wei, Professor, Tsinghua University；
Co-Chair: Yalin Liu, University of Science and Technology Beijing
Speech:
Intelligent Construction of Cement Concrete Pavement----Integrating Modern Slipform Machinery with Advanced Cement Concrete Material Science
Zhi Fu, Research Professor, Research Institute of Highway, Ministry of Transport
Weak Form Quadrature Element Analysis of Cracked Thin Plates
Hongzhi Zhong, Professor, Tsinghua University
Multi-objective Optimization, Enhancement Mechanism and Engineering Applications of High Performance Porous Concrete
Mulian Zheng, Professor, Chang'an University
A Preliminary Exploration of Several Technical Issues in Road Maintenance
Qun Yang, Professor, Tongji University
Integrated Intelligent Detection and Analysis of Hidden Defects in Rigid Pavements
Ya Wei, Professor, Tsinghuan University

Parallel Session F2

Topic: Deterioration Behavior and Durability Enhancement Technologies of Cement Concrete Pavement

Chair: Zhengfeng Zhou, Associate Professor, Southwest Jiaotong University

Speech:

Dynamic Mechanical Response of Full-Scale Pavement Structures under Heavy Loading

游庆龙

Extension and Conversion of Technical Condition Evaluation System for Road Structures

周正峰

Extension and Conversion of Technical Condition Evaluation System for Road Structures

李聪

Yield Criterion of High-Performance Porous Concrete

曲广雷

Dynamic Mechanical Response of Full-Scale Pavement Structures under Heavy Loading

Qinglong You,
Chang'an University

报告摘要：

公路路网具有密度高，覆盖范围广，有一定的承载能力，是理想的发射场地，采用公路发射成为机动发射的一种方式，发射装备产生的冲击荷载使得路面产生大变形，影响发射出筒姿态，无法保障装备的安全使用，因此如何准确评价路面结构的承载能力，对保障发射装备的安全使用具有重要价值。

为掌握发射装备大冲击荷载作用下道路结构力学行为，针对某型号发射装备，修筑了 7 种代表性典型路面结构，采用自主研制的等效荷载当量激发装置，同时在路面各结构层埋设竖向变形、土压力等传感器，实时采集大冲击荷载作用下道路结构力学响应，完成了 13 次足尺大冲击荷载作用下道路结构力学响应试验，揭示了大冲击荷载作用下道路结构力学行为，获得了大冲击荷载作用下道路结构变形规律，掌握了发射装备的应用边界条件，为更好的服务国防事业提供了行业智慧。

Damage-Fracture Model for Cement Concrete

Zhengfeng Zhou
Southwest Jiaotong University

报告摘要：

报告介绍了基于牵引力-分离法则的黏聚区模型的本构、参数及应用。牵引力-分离法则黏结单元实际上表征的是单元 2 个相对面之间的应力与法向或切向相对位移的关系，可用于模拟断裂力学中的张开、剪切或撕开断裂。牵引力-分离法则将单元受力直至失效所受牵引力与张开位移分为线弹性、损伤和失效 3 个阶段。报告介绍了黏结单元线弹性刚度、极限应力、断裂能和损伤因子等本构参数的确定方法，以及在路面开裂分析、试件细观断裂分析中的建模方法。

Evaluation and Improvement Directions for ACR-PCR of Airport Cement Pavement Bearing Capacity

Lukuan Ma,
Civil Aviation University of China

报告摘要：

道面承载能力评价是保障飞机安全运行的重要工作之一。在回顾 ACN-PCN 评价方法基本原理和计算并总结其局限性的基础上，阐述了 ACR-PCR 评价方法的优化内容，明确了 ACR 和 PCR 的计算方法，并通过算例对比分析了两种方法，同时提出了改进方向。结果表明，ACR-PCR 评价方法改进了标准结构、破坏模式与控制准则、力学响应计算方法、当量单轮胎压等要素，实现了与现行设计方法的统一；ACR 值不能简单地用 10 倍的 ACN 值表示，并且 ACR-PCR 评价方法对刚性道面承载能力提出了更高要求；建议在优化标准结构的基础上，提出针对无机结合料稳定类基层道面的飞机 ACR 计算方法以及刚性道面上加铺层复合道面承载能力 ACR-PCR 评价方法。

Extension and Conversion of Technical Condition Evaluation System for Road Structures

Cong Li
Guilin University of Electronic Technology

报告摘要：

突破现行道路基础设施性能评价偏重于结构安全的局限，从技术性态与服务质量两向测度，构建面向“结构安全状态”、“设施使用性能”与“驾乘服务质量”三个维度的道路结构运行状态指标体系。基于多元化聚类分析原理，建立道路结构服役性态综合评价通用转换机制，即将个数较多、物理意义各异、测试方法差别较大的检/监测参数转换为个数较少、可资比较的聚类因子，从而解决在统一标准下，路网内各路段综合服役性态的排序难题。

Yield Criterion of High-Performance Porous Concrete

Guanglei Qu,
Chang'an University

报告摘要：

高性能多孔混凝土（HPPC）因具有跨尺度空隙特征，其力学行为难以用传统连续介质模型准确描述。本文基于细观损伤力学与弹塑性理论，建立并修正Gurson 屈服准则，以揭示 HPPC 在单轴及三轴应力下的力学特性。研究表明：单轴条件下，HPPC 的应力-应变曲线呈现弹性、塑性、破坏及残余阶段；三轴应力条件下，破坏模式由拉伸向剪切转变，围压与纤维显著提升延性与峰值应力，空隙率提高显著降低 HPPC 承载力。修正的四参数 Gurson 屈服准则能合理表征HPPC 屈服行为，验证结果显示其适用性与准确性良好。

Parallel Session G1

Topic: Sustainability and Resilience for Road Infrastructure-1

Chair: Hui Li, Professor,Tongji University; Co-Chair: Cong Ma, Professor, Tongji University

Introduction:

Climate change, driven by anthropogenic forcing, is fundamentally altering our planetary systems, manifesting in heightened frequency and severity of extreme hydrogeological and meteorological events. Catastrophic floods, destabilizing landslides, pervasive coastal erosion, and thermal extremes now pose immediate and escalating threats to the operational integrity, safety, and long-term reliability of global road networks. These disruptions cascade through socioeconomic systems, compromising supply chains, impeding emergency response, and diminishing societal mobility. Confronting these interconnected challenges necessitates an urgent paradigm shift towards holistically sustainable and resilient road infrastructure. This imperative demands integrated approaches encompassing design, construction, operation, and maintenance to minimize lifecycle environmental impacts while endowing infrastructure with the intrinsic capacity to anticipate, absorb, adapt to, and rapidly recover from acute shocks and chronic stressors. This critical forum session convenes leading experts to explore transformative innovations pivotal to this transition. Our discourse will rigorously examine advancements in low-carbon, high-durability materials including novel binders, advanced composites, optimized concrete formulations, high-incorporation recycled aggregates, and self-healing technologies – essential for reducing embodied carbon and extending asset longevity. Concurrently, we will address sophisticated resilience enhancement strategies, spanning engineered solutions for robust drainage, slope stabilization, and flood mitigation, alongside nature-based approaches and adaptive design principles, underpinned by predictive asset management systems leveraging big data analytics. Integral to this progression is the advancement of robust assessment methodologies, incorporating life cycle assessment (LCA), comprehensive carbon accounting, probabilistic risk modeling, vulnerability quantification, and post-disruption performance metrics, all calibrated using forward-looking climate projections. Join us to shape the future of infrastructure that is environmentally responsible, inherently durable, and engineered for resilience in an era of unprecedented climatic volatility.

Speech:

Trenchless Resilient Rehabilitation Technology for Deep-Seated Road Defects

Yanhui Zhong, Bei Zhang, School of Water Conservancy and Transportation, Zhengzhou University

中交集团绿色低碳发展探索与实践

张帆，中交集团绿色低碳发展研究中心/中交公路规划设计院有限公司

Construction, Practice and Development of Green Transportation Standard System

Ji Wang, Wei Wang, Standards and Metrology Research Center, China Academy of Transportation Sciences

The Impact of High-Impact Weather on Transportation under the Background of Climate Change

Wang Hongbin, Liu Duanyang, Zhang Zhiwei, Zhu Shoupeng, Zu Fan, Nanjing Innovation Institute for Atmospheric Sciences, Chinese Academy of Meteorological Sciences–Jiangsu Meteorological Service

Research and Practice on Green and Low-Carbon Preventive Maintenance Technology for Asphalt Pavements of Shanxi Expressways

Hengji Zhang, STHG Technology Transformation Co., Ltd

Trenchless Resilient Rehabilitation Technology for Deep-Seated Road Defects

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Graphical abstract

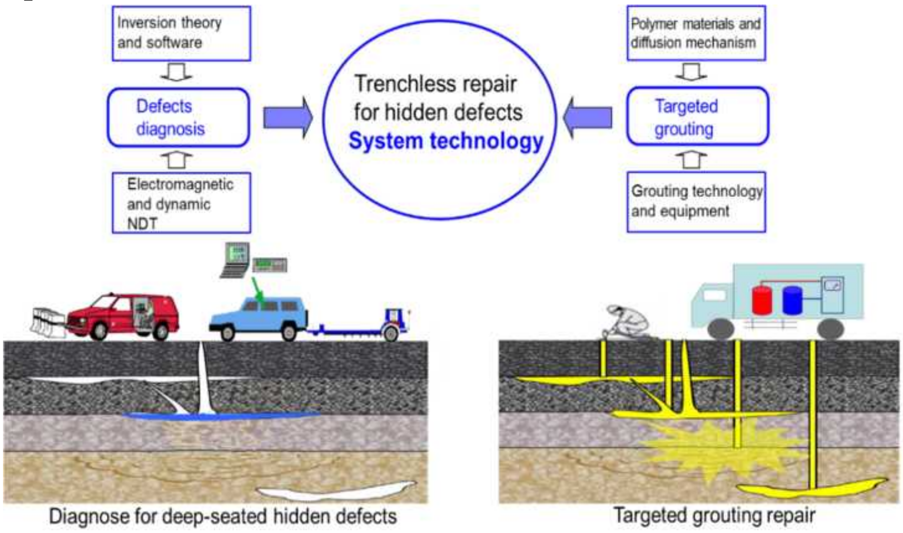

Figure 1 Trenchless Resilient Rehabilitation Technology for Deep-Seated Road Defects

3.1 Objectives and Methodology

To address the high maintenance demands of China's vast road network and the challenges of diagnosing/treating water-induced structural damage, a novel trenchless resilient rehabilitation technology is developed. This system combines three key innovations:

(1) Seepage-resistant resilient materials (non-water-reacted polymer grouting compounds. two types: expansive polymer and penetrative polymer);

(2) Precision damage diagnostics (non-destructive testing and inverse theory);

(3) Targeted polymer grouting technology.

3.2 Major results and findings

The process of the trenchless resilient rehabilitation technology is as figure 2. It begins with non-destructive detection of subsurface damages or defects, followed by polymer grouting that:

(6) Drains water or mud;

(7) Fills voids and cracks ;

(8) Reinforces loose structures;

(9) Lifts and levels sunken/settled pavement structures.

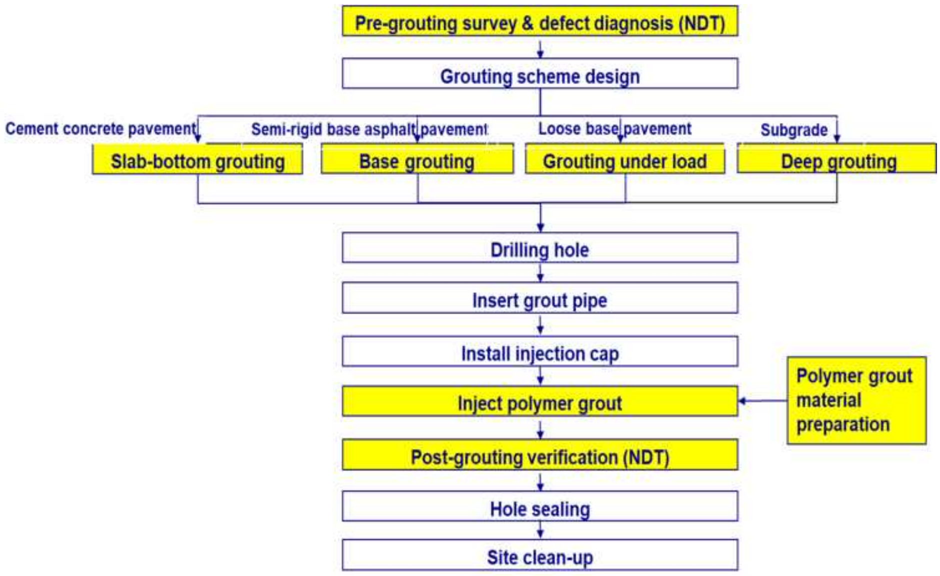

Figure 2 Process of Polymer Grouting Rehabilitation Technology
for Deep-Seated Hidden Road Defects

This integrated solution offers complete, excavation-free repair that addresses root causes rather than symptoms. Key advantages include:

(1) Rapid application;
(2) Long-lasting results;
(3) Cost-effectiveness;
(4) Eco-friendly operation.

中交集团绿色低碳发展探索与实践

张帆[1]

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中交集团作为全球领先的特大型基础设施综合服务商，业务覆盖157个国家和地区。2023年新签合同额25902亿元，连续十八年位居ENR全球最大国际承包商中国企业首位。为响应国家“双碳”战略，集团构建了完善的绿色低碳管理体系：2021年成立绿色低碳发展领导小组，2022年设立绿色低碳发展研究中心及碳资产管理中心，整合技术研发、碳核算、碳交易等专业力量，形成“战略规划 - 技术研发 - 工程实践 - 标准输出”的全链条能力。

一、顶层设计

集团印发《中交集团绿色低碳行动方案》（提出“11568”发展路径）、《“十四五”绿色低碳发展规划》等文件，构建“1+N”管理制度体系，涵盖考核评价、碳资产管理等7项核心制度。深度参与国资委绿色低碳评价体系构建，将考核结果纳入经营业绩评估，推动全产业链协同减碳。

二、绿色低碳示范工程实践

2023-2025年累计打造42项绿色低碳示范工程，覆盖公路、水运、生态修复等7大领域。其中，承平高速雾灵山零碳服务区入选交通部首批零碳试点，川藏铁路、西部陆海新通道等项目形成“零碳服务区”“离岸深水港”等技术突破。国际项目中，埃塞俄比亚亚的斯亚贝巴环城路入选联合国“全球可持续交通最佳实践案例”，带动区域物流效率提升30%，创造数万个就业岗位。

三、技术突破与标准输出

发布200项绿色低碳工艺工法及32项核心技术成果，其中“江河湖库生态清淤技术”等2项入选发改委绿色技术目录。构建公路、桥梁、水运等6大领域技术图谱，涵盖32个子方向、70项成套技术，约215个关键技术点。牵头制定国家标准10余项、行业标准10余项，企业标准20余项，公路工程碳排放计算方法获卢森堡专利，推动中国标准国际化。

四、绿色低碳装备升级

自主研发国内首艘LNG双燃料动力万吨级耙吸挖泥船“新海鲟”号，全生命周期减碳74万吨；“浚清”号填补清洁能源疏浚船舶空白，港口设备推广电能、氢能应用。

五、碳资产管理与金融创新

推出交通领域首个CCER方法学，建立内部碳交易机制，2024年完成国内基建行业首单内部碳交易，2025年扩大试点至多方主体交易。探索“蓝碳”交易，2023年完成广西首宗红树林碳汇交易。金融领域主编国内首个交通转型金融标准，落地国道111线等转型金融项目，降低融资成本超千万元。

六、数字化平台建设

数字双碳平台（一期）试运行，实现绿色低碳工作全流程线上管理等；自主研发碳排放测算软件。

七、产品碳足迹核算和认证

获港机领域首张碳足迹核查证书，覆盖轮胎吊全生命周期。

八、产业拓展与成效

布局新型储能、海上风电等绿色产业，获760万千瓦抽水蓄能电站开发权，海上风电市场份额超50%；光伏发电项目累计产绿电3亿度，减碳30万吨。

2024 年，中交集团获评国资委“传统产业绿色转型考核第一”“交通基础设施绿色低碳原创技术策源地”，入选中国工业碳达峰“领跑者”企业，4 家水厂成为全国首批绿色低碳标杆厂。中交集团通过技术创新、工程实践与制度创新，持续推动基础设施领域绿色低碳转型，为全球可持续发展提供“中国方案”。

Construction, Practice and Development of Green Transportation Standard System

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Graphical abstract

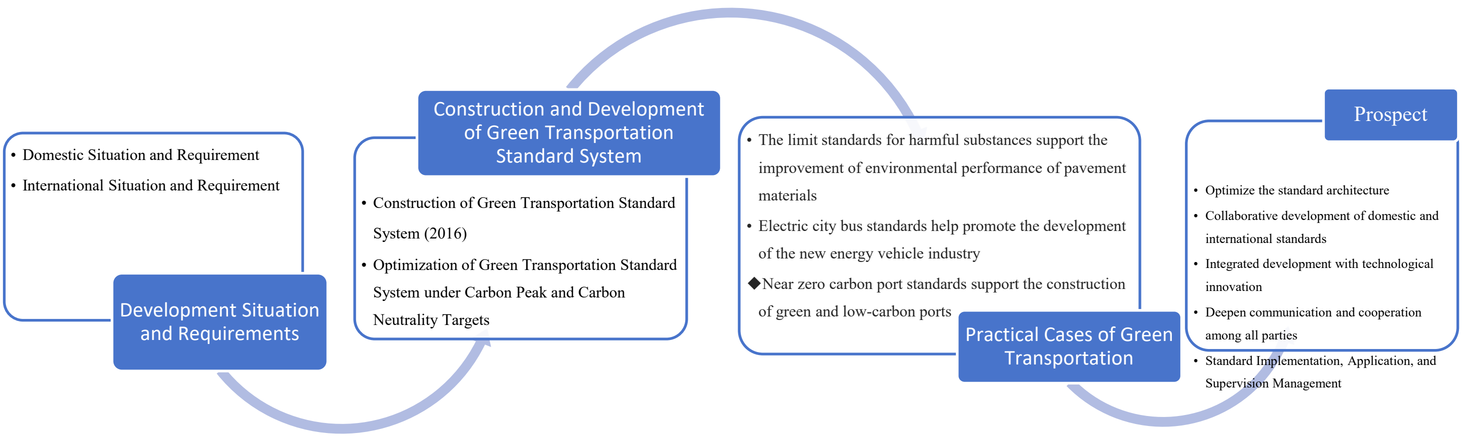

Figure 1 Graphical abstract

5.1 Objectives and Methodology

Currently, the development of green and low-carbon industries, as a crucial aspect of promoting economic restructuring, places higher and more urgent demands on the construction of green transportation. Standardization plays a vital role in advancing the "dual carbon target" and promoting the development of green transportation. To explore how standardization can support and guide the coordinated development of decarbonization, pollution reduction, greening, and growth, this study builds on the team's involvement in supporting the Ministry of Transport in drafting the *Green Transportation Standard System*. Employing methods such as problem-oriented demand analysis, standard indicator comparison, system optimization and adjustment, and case deconstruction, the study presents the construction process of the *Green Transportation Standard System*. Starting from the demands placed on green transportation standards by "dual carbon target", a demand indicator system is developed, followed by comparison with existing standards and analysis of key standards, leading to further optimization of the standards system. In addition, representative practical cases of green transportation standardization are analyzed. It is hoped that this work will encourage more researchers, policy makers, and industry professionals to engage in the research, development, and application of green transportation standards.

5.2 Major results and findings

Introduce the major research results and findings with table and charts.

Table 1 Table name

1. Since the implementation of the *Green Transportation Standard System*, both the speed and quality of national and industry standard

development for green transportation have significantly improved. During the 13th Five-Year Plan period, the number of national and industry standards increased by 116%.
2. Under the "dual carbon target", the development of the green transportation standard system should place greater emphasis on the coordinated advancement of decarbonization, pollution reduction, greening, and growth. Continued efforts are needed to optimize the structure of the standards system, enhance alignment with international standards, promote the integration of standards with technological innovation, deepen multi-stakeholder communication and cooperation, and strengthen the implementation, application, and supervision of standards. These measures will provide stronger support for the comprehensive green and low-carbon transformation of the transportation sector.

The Impact of High-Impact Weather on Transportation under the Background of Climate Change

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2 Key Laboratory of Transportation Meteorology of CMA/ Jiangsu Key Laboratory of Severe Storm Disaster Risk, Nanjing 210041, China

Abstract

Transportation, as a fundamental and pioneering industry of the national economy, its safe and efficient operation is closely related to meteorological conditions. However, against the backdrop of climate change, the frequency of extreme weather events (such as heavy rainfall, dense fog, low-temperature snow and ice, etc.) has significantly increased. Data from 1961 to 2024 shows that the frequency of extreme daily precipitation events in China is on the rise, which has led to frequent occurrence of major traffic accidents, traffic disruptions and facility damage, seriously restricting the safety and efficiency of the transportation system. Therefore, it is of great practical significance to carry out research and development on key technologies for transportation meteorological services

1 Objectives and Methodology

The present study aims to enhance the capability of transportation meteorological services under high-impact weather conditions. By combining methods of observational experiments, equipment development, model construction and technical application, it focuses on solving the monitoring and early warning methods for traffic high-impact weather such as dense fog, pavement conditions and heavy precipitation, so as to provide technical support for the safe operation of transportation systems.

2 Major results and findings

（1）Visibility

This study has conducted field scientific experiments on dense fog, established a scientific experiment dataset of dense fog, and formed a comprehensive three-dimensional observation experiment scheme for dense fog disaster processes. It has discovered the phenomenon that the frequent dense fog areas in Jiangsu Province are moving northward and revealed the macro and micro characteristics of different grades of fog in Jiangsu. By integrating information such as the boundary layer structure of different grades of fog, a fog classification recognition algorithm based on satellite data has been created, which realizes the differentiation between low clouds and fog through satellite remote sensing and improves the recognition accuracy of dense fog. Additionally, by matching with traffic interruption data, the impact of meteorological factors on traffic interruption events has been analyzed.

(1) Pavement temperature

To address the shortcomings of current pavement temperature forecasting, this study, based on numerical model forecasts, data from traffic meteorological stations and mobile test vehicles, and by combining dynamic models with statistical principles, proposes a short-term pavement temperature forecasting model based on Stepwise Regression-Model Output Statistics (SRMOS). This model effectively improves the accuracy of pavement temperature forecasting, reducing the forecasting error by 0.7–1.6°C compared with the original single-factor forecasting model. It also reveals the importance of temperature, humidity, and large-scale circulation as collaborative forecasting factors for pavement temperature, realizing the effective conversion and correction of meteorological element forecasts from numerical models to pavement temperature forecasts.

The study pioneered the provincial-level high-resolution (20-meter) highway thermal spectrum map technology, and based on this technology, established a pavement low-temperature early warning model to realize the monitoring and early warning of winter pavement icing conditions. The traffic meteorological disaster dynamic monitoring and early warning system applied on Suzhou Expressway can predict pavement temperature in advance, reducing operation and maintenance manpower by 27.11% and improving operation efficiency by 32.79%.

Research and Practice on Green and Low-Carbon Preventive Maintenance Technology for Asphalt Pavements of Shanxi Expressways

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Graphical abstract

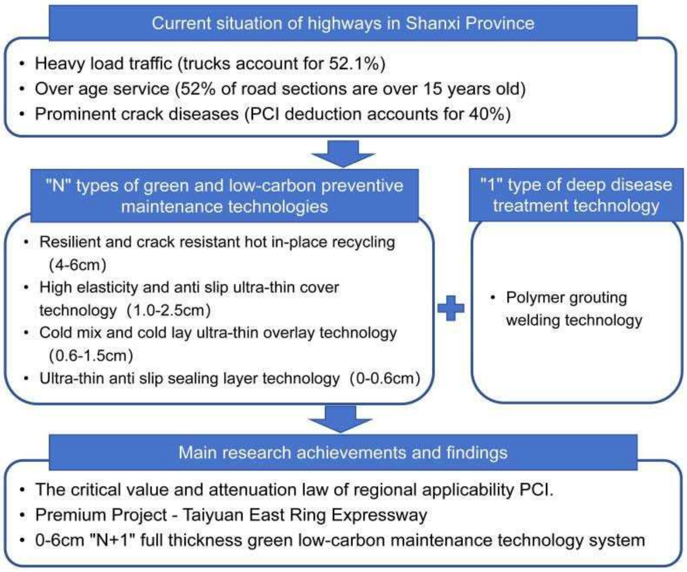

Figure 1 Graphical abstract

Objectives and Methodology

Objectives: To solve the contradiction between the surge in maintenance demand and limited funds caused by heavy load traffic (trucks account for 52.1%), over age service (52% of road sections are over 15 years old), and prominent crack diseases (PCI deduction accounts for 40%) on Shanxi highways, we will develop a green, low-carbon, and economically efficient asphalt pavement preventive maintenance technology system that is in line with Shanxi's characteristics, extend the service life of the pavement, and reduce the full life cycle cost.

Methodology: Build a "0-6cm 'N+1' full thickness green and low-carbon maintenance technology system".

"N" types of green and low-carbon preventive maintenance technologies: focusing on the development of road surface diseases (0-6cm), with a focus on:

Resilient and crack resistant hot in-place recycling (4-6cm): achieved high-performance reduction, toughening, and regeneration of aged asphalt.

High elasticity and anti slip ultra-thin cover technology (1.0-2.5cm): High toughness crack resistance, anti slip and noise reduction.

Cold mix and cold lay ultra-thin overlay technology (0.6-1.5cm): High viscosity emulsified asphalt, high oil stone ratio, anti reflective cracking.

Ultra-thin anti slip sealing layer technology (0-0.6cm): Enhances the ability to resist loosening and peeling, with fast construction speed, suitable for bridge and tunnel areas.

"1" type of deep disease treatment technology: For stubborn semi-rigid base reflection cracks, sufficient filling and structural repair are carried out.

Major results and findings

Table 1 Comparison Table of PCI (Pavement Condition Index) Attenuation in Shanxi Region Division

Regional division	PCI (Pavement Condition Index)				PCI attenuation value after completion		
	original pavement	After completion	Freeze thaw period (1 quarter)	Opened for one year	Freeze thaw period (1 quarter)	Non freezing and thawing period (3 quarters)	Opened for one year
	Provincial Inspection in 2022	Provincial Inspection in 2023	Q1 of 2024	Provincial Inspection in 2024			
North(184,300m²)	79.2	97.7	88.4	85.8	9.3	2.6	11.9
Central(690,500m²)	86.9	99.0	96.3	94.7	2.7	1.7	4.3
South(124,300m²)	88.9	98.7	95.7	96.2	3.0	-0.5	2.5
Average value	85.0	98.5	93.5	92.2	5.0	1.3	6.3

Note: The data is sourced from the detection data of 1 million In-place Hot Recycling implemented in Shanxi Province in 2023.

Table 2 Comparison Table of In Situ Thermal Regeneration and Milling Repainting (Single Layer) PCI for Asphalt Pavement

Serial Number	Construction technology	South		Central		North	
		Hot in-place recycling	Milling and repaving (Single layer)	Hot in-place recycling	Milling and repaving (Single layer)	Hot in-place recycling	Milling and repaving (Single layer)

1	Before implementation(2022)	84.0	81.5	86.0	87.3	79.2	75.3
2	After implementation(2023)	98.5	93.5	100	100	96.9	95.3
3	After one year of implementation(2024)	98.5	93.3	96.4	97.8	86.4	92.1
4	Compared to before construction (2024-2022)	14.5	11.9	10.4	10.5	7.2	16.8
5	Decay within one year of completion (2023-2024)	0.0	0.2	3.6	2.2	10.5	3.2

Note: The data is sourced from the detection data of 1 million In-place Hot R ecycling implemented in Shanxi Province in 2023.

Parallel Session G2

Topic: Sustainability and Resilience for Road Infrastructure-2

Chair: Hui Li, Professor, Tongji University; Co-Chair: Cong Ma, Professor, Tongji University

Introduction:

Climate change, driven by anthropogenic forcing, is fundamentally altering our planetary systems, manifesting in heightened frequency and severity of extreme hydrogeological and meteorological events. Catastrophic floods, destabilizing landslides, pervasive coastal erosion, and thermal extremes now pose immediate and escalating threats to the operational integrity, safety, and long-term reliability of global road networks. These disruptions cascade through socioeconomic systems, compromising supply chains, impeding emergency response, and diminishing societal mobility. Confronting these interconnected challenges necessitates an urgent paradigm shift towards holistically sustainable and resilient road infrastructure. This imperative demands integrated approaches encompassing design, construction, operation, and maintenance to minimize lifecycle environmental impacts while endowing infrastructure with the intrinsic capacity to anticipate, absorb, adapt to, and rapidly recover from acute shocks and chronic stressors. This critical forum session convenes leading experts to explore transformative innovations pivotal to this transition. Our discourse will rigorously examine advancements in low-carbon, high-durability materials including novel binders, advanced composites, optimized concrete formulations, high-incorporation recycled aggregates, and self-healing technologies – essential for reducing embodied carbon and extending asset longevity. Concurrently, we will address sophisticated resilience enhancement strategies, spanning engineered solutions for robust drainage, slope stabilization, and flood mitigation, alongside nature-based approaches and adaptive design principles, underpinned by predictive asset management systems leveraging big data analytics. Integral to this progression is the advancement of robust assessment methodologies, incorporating life cycle assessment (LCA), comprehensive carbon accounting, probabilistic risk modeling, vulnerability quantification, and post-disruption performance metrics, all calibrated using forward-looking climate projections. Join us to shape the future of infrastructure that is environmentally responsible, inherently durable, and engineered for resilience in an era of unprecedented climatic volatility.

Speech:

大模型驱动的公路交通基础设施灾变预警

Bowen Du, Junchen Ye, School of Transportation Science and Engineering, Beihang University

Exploration of Integrated Space-Air-Ground Monitoring and Early Warning Technology for Transportation Infrastructure Safety

Zhongqi Shi, National Science and Technology Institute of Urban Safety Development

Perception and Practice of Highway Abnormal Event Detection and Early

Warning
Yandong Zhao, associate research fellowIntelligent Road Cloud Transportation Science &Technology Company
Ecology and Resilience of Transportation Infrastructure: Theory and Practice
Hui Li, College of Transportation, Tongji University

大模型驱动的公路交通基础设施灾变预警

Bowen Du [1], Junchen Ye [2]

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[2] School of Transportation Science and Engineering, Beihang University, Beijing, 100191 China, junchenye@buaa.edu.cn

Graphical abstract

Figure 1 Graphical abstract

8.1 Objectives and Methodology

8.1.1 研究目的

当前我国公路里程已经突破 549 万公里，其中高速公路超 19 万公里，高速公路网建设取得了举世瞩目成就。与此同时，我国也是世界上自然灾害最为严重国家之一，2023 年由滑坡、水毁、塌陷等路基灾害造成的直接经济损失高达 2445.7 亿元，灾害后果严重。

基础设施灾变预警涉及传感器、视频、气象、地质等多种数据类型，来源不同、格式各异，传统方法难以实现数据统一处理；现有方法多针对单一模态优化，缺乏有效的跨模态特征融合机制，导致多源信息利用受限，无法发挥数据协同价值。为此，急需破解多源异构数据融合难题，构建统一的跨模态预警体系，实现大模型驱动的时空编码多源数据耦合与跨模态预警的一体化预测预警方法。

8.1.2 发展机遇与发展现状

大模型通常指的是具有大量参数和复杂结构的深度学习模型，其优势在于可以更准确地模拟和分析公路中的实际问题，有助于提高设计精度，优化施工方案，并降低工程风险，预警灾害发生。现有工程大脑建设尚处于“单任务+单模型”的研发模式；然而人工智能领域已朝“通用表征+全场景化赋能”模式发展，将大模型应用于基础设施性态演化的任务已成为必然趋势。

提示词工程(Prompt)是用于引导大语言模型生成特定输出的输入提示，合理的 Prompt 可以有效激发模型内部知识、控制输出内容和风格，引导大语言模型生成更符合预期的结果。提示词在用户输入之外构建一个结构化自然语言描述用于指导大语言模型的输出，可以有效提升大模型输出结果的准确性。

检索增强生成技术（RAG）定义了大模型如何通过检索外部及实时的知识，来生成更精准且有据可查的回答。这一机制有效弥补了通用大模型知识过时和内容幻觉的缺陷，显著提升了大模型在垂直领域的实用性与可信度。

思维链（CoT）通过模拟人类解决复杂问题时的思考过程，引导大语言模型在生成答案的过程中引入一系列的中间推理步骤。这种方法能够显著提升模型在推理任务上的表现，而且还能揭示模型在处理复杂问题时的内部逻辑和推理路径。

自主智能体（Agent）是一种能够在特定环境下独立运行，并具备自主性、反应性、主动性、社会性等特性的智能实体。它可以根据自身知识和环境信息，主动地执行动作、做出决策，并与其它智能体或人类进行交互和协作，以完成特定的任务或目标。

上下文协议（MCP）模型定义了 AI 模型（比如大型语言模型 LLM）如何与外部世界（各种工具、服务、数据）安全、高效地交互。通过 MCP 的加持，各类 Agent 可以被连接起来，以实现一个复杂的、类人行为的复杂工作流。

8.2 Major results and findings

设计开发了基于 AI 大模型的公路设计与运维系统。针对领域知识复杂多源难以统一问题，该系统基于通用大模型进行知识抽取，智能构建知识图谱，引入结构化关系信息，提升了领域专用模型对外接知识库的利用能力，从而实现外接知识库的智能图谱化，保留领域实体结构关系。针对知识图谱内容复杂，领域知识深度关联，普通大模型回答精度较差问题，提出面向公路知识图谱的双层检索策略，进一步设计了公路领域化图谱-RAG 框架，实现公路设计运维高效知识关联与精准决策支持，增强了大模型对于概括性以及知识关联性问题的回答表现。此外，基于公路垂类语料库，应用 MLM(填补) 与 CLM(续写)两类任务，采用 LoRA 高效微调技术，实现了通用模型向公路垂类模型的低成本参数更新与迁移。

探索了路基-边坡突发灾害大模型构建与灾变场景自主认知方法。针对多模态数据难以协同表征的问题，建立了突发灾害下路基-边坡沉陷、崩塌、滑坡等灾变相关的多模态特征提取、数据对齐、一致化表征及特征增强方法，突破了大模型输入数据维度、密度、采集频率差异造成的理解与融合难题；建立了基于扩散生成模型的灾变全过程还原技术，通过正向逐步加噪，再学习逆向去噪过程，实现了对复杂数据的精准建模，实现灾变过程时序还原。针对当前大模型多为通用大模型，难以适配特定场景问题，提出了数值、知识表征和机理约束联合训练方法，采用知识机理内嵌，增强大模型对领域知识理解能力，在跨模态多层次联合训练预测，攻克小样本环境下大模型训练技术瓶颈，增强模型对领域知识的理解能力。

研发了基于生成式大模型的路基-边坡突发灾害超前预警技术。根据公路场景多任务、多隐患的特点，采用多领域专家模型库与多智能体协同决策架构，增强复杂场景下的问题识别与隐患处理能力；建立了阈值自适应的超前时序预警技术，研制多模态数据接入-多领域知识嵌入-多专家决策-多场景适配的突发灾害超前预警大模型平台，显著提升路基-边坡突发灾害预警准确性与响应能力。

Exploration of Integrated Space-Air-Ground Monitoring and Early Warning Technology for Transportation Infrastructure Safety

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[1] National Science and Technology Institute of Urban Safety Development, 518000 China, shizq@szsti.org

Graphical abstract

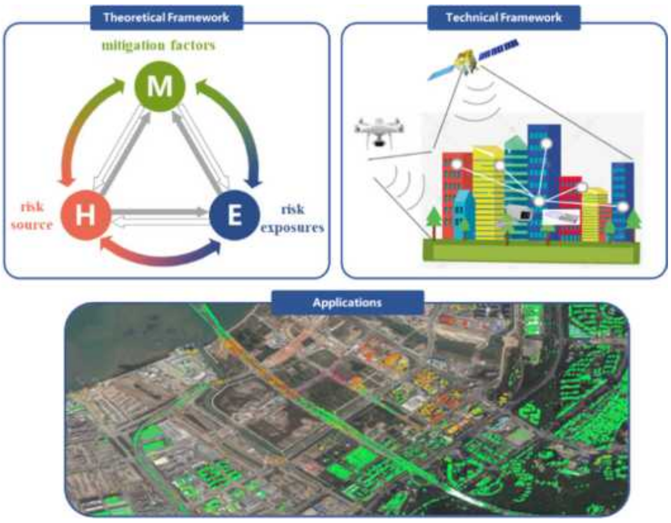

Figure 1 Graphical abstract

9.1 Objectives and Methodology

The rapid urbanization and increasing complexity of modern cities have heightened the demand for advanced monitoring and early warning systems to ensure the safety and resilience of transportation infrastructure. This study aims to address the limitations of traditional monitoring methods by developing an integrated Space-Air-Ground framework. The methodology combines satellite remote sensing, UAV-based inspections, and ground-based distributed sensing technologies to achieve comprehensive, real-time, and high-precision monitoring.

9.2 Major results and findings

First, the HEM framework considering all urban safety elements provides the basic theory for transportation infrustructure safety management. The risk source (H)- risk exposures (E)- mitigation factors (M) framework provides an approach to match urban safety elements with urban safety needs, as well as a quantitate tool to evaluate the urban safety.

Second, the integration of spaceborne InSAR monitoring with domain-specific knowledge in transportation infrastructure enables large-scale deformation screening for extensive areas. In terms of improving InSAR scatterer density, this study introduces TomoSAR based on conventional time-series InSAR algorithms. By employing a region-growing algorithm, the connectivity of the dual-layer PS verification network was enhanced. Furthermore, the beamforming tomography algorithm was applied to achieve refined elevation estimation of scatterers. These integrated approaches collectively doubled the scatterer density in three-dimensional space. To address the issue of low positioning accuracy, a SAR-LiDAR fusion-based phase estimation refinement method was developed, which significantly improved the 3D positioning precision of InSAR observation points. This approach achieved remarkable reductions in positioning offsets - 33%-79% for planar coordinates and 53%-90% for elevation measurements.

Third, by integrating spaceborne InSAR screening with airborne-ground intelligent monitoring, the technology was applied to typical transportation infrastructure in megacities. A total of 10 bridges in Shenzhen's western reclamation area were monitored, successfully identifying pile settlement and girder slippage along the Yanjiang Expressway bridges. This approach supported emergency engineering projects by providing road network inundation analysis during Shenzhen's rainstorm emergency response.

In the future, we will further break through the technical bottlenecks in Space-Air-Ground monitoring methods, and integrated fusion systems to achieve comprehensive, efficient, and precise space-air-ground integrated monitoring and early warning for road-bridge networks. Addressing the discrete, sudden, hidden, and complex nature of road and bridge safety risks, we will adopt a "macro theory-methodology system-technical means" integrated approach to ensure the operational safety of extensive transportation infrastructure and prevent major accidents.

Perception and Practice of Highway Abnormal Event Detection and Early Warning

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Technology Company, Beijing, China, ydzhao010@qq.com

Graphical abstract

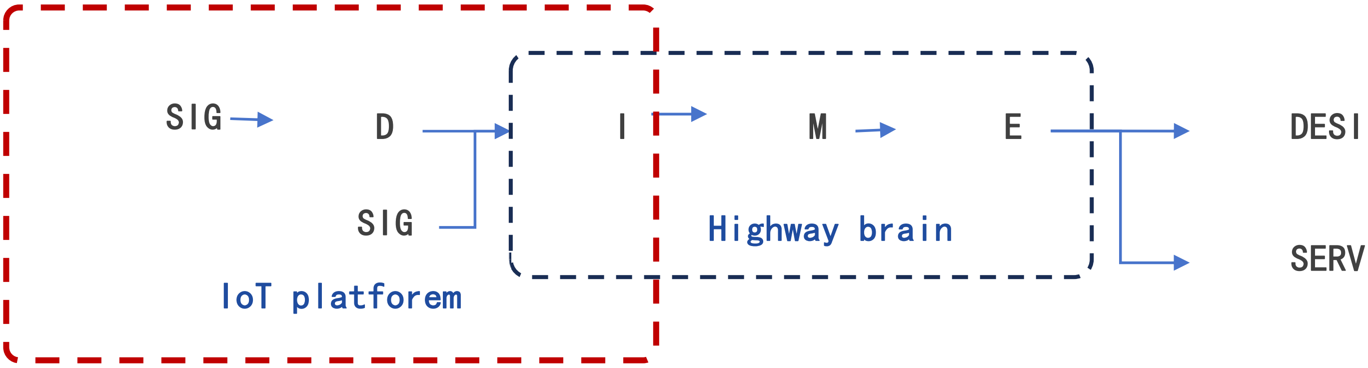

Figure the framework of detection and applications

10.1 Abnormal Event Detection and Applications

Highway Abnormal Event Detection and early warning external field equipment is seriously dependent, but the cost of electromechanical equipment and system construction, operation and maintenance and replacement is relatively high. How to achieve low-cost and high coverage perception under limited conditions is one of the main challenges facing the industry at present. At the same time, in the construction of smart highways, digital transformation and upgrading or independent monitoring and early warning projects, monitoring and early warning are important contents. It is also necessary to avoid fragmentation of projects and capabilities, establish a monitoring and early warning system with "consistent standards, connecting up and down, interconnecting left and right, and empowering the whole" to integrate various perception means in the road network to form a road network-level intelligent capability of "full-domain perception, full-network collaboration, and full-process service".

10.2 Major results and findings

Low-cost high-coverage perception system

Table 1 Innovations

Low-cost high-coverage perception system
Multi-source heterogeneous data fusion
Criteria for grading and classification of exception events based on structured data
Digital link from perception to application

Ecology and Resilience of Transportation Infrastructure: Theory and Practice

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Graphical abstract

Figure 1 Framework and Methodology of Emergency Repair and Rapid Recovery for Transportation Infrastructure After Disasters

1 Objectives and Methodology

This project adopts a safety-efficiency-economy oriented approach, targeting two major regions, two types of facilities, three structural categories, and nine disaster scenarios. Focusing on full-chain technological innovation across "disaster assessment → emergency repair decision-making → rapid traffic restoration", it conducts research in five key areas:

(10) Three-dimensional detection and assessment;
(11) Emergency repair decision-making for critical transport corridors;
(12) Rapid traffic restoration for roads and bridges;

(13) Targeted tunnel reinforcement;
(14) Resilient rehabilitation of damaged components.

2 Major results and findings

The scientific research for Task 2 led by Tongji University, leveraging a three-tier R&D demonstration system of laboratory development → full-scale pilot testing → engineering validation, has delivered comprehensive integrated innovations:

(5) Establishing a multi-scale, multi-process simulation platform to reconstruct disaster scenarios;

(6) Revealing structural failure mechanisms and rapid reinforcement principles for all structural types under multiple disasters;

(7) Developing a multi-objective optimization model balancing efficiency-safety-economy;

(8) Creating a dynamic decision-making system featuring multi-tiered, multi-objective, multi-agent coordination.

This provides theoretical underpinnings for post-disaster rapid emergency repair operations.

Parallel Session H1

Topic: Low-carbon and Durable Polyurethane-based Paving Materials and Technology

Chair: Shifa Xu, Professor, Beijing University of Civil Engineering and Architecture

Introduction:

The theme of this session is the application and development of polyurethane materials in road engineering. Traditional hot-mix asphalt mixtures consume large amounts of fuel and emit substantial exhaust gases during production and construction, resulting in significant resource waste and environmental pollution.

Polyurethane, synthesized from isocyanates and polyols, is a multifunctional polymer material with advantages such as high performance, long service life, and energy efficiency with environmental benefits. It has been widely applied in construction, transportation, and industrial manufacture. In recent years, polyurethane has gradually replaced asphalt, emerging as a new generation of road paving material.

The following four presenters will introduce the application and development of polyurethane materials, focusing on noise reduction performance, service life, recycling of reclaimed materials, and performance comparison with conventional asphalt mixtures. The four presentation titles are as follows:

1 Noise-Reducing Polyurethane Porous Elastic Mixture: Development, Water Stability, and Aging Resistance.

2 The Performance and Application Prospect of Polyurethane Modified Asphalt Reclaimed Pavement with 100% RAP.

3 Development and Typical Application of Polyurethane Based Paving Material.

4 Effect of the Thermal-Oxidative Aging on the Road Performance and Noise Reduction Ability of Polyurethane Porous Elastic Road Surface.

Speech:

Noise-Reducing Polyurethane Porous Elastic Mixture: Development, Water Stability, and Aging Resistance

Shuangyan Zhang, Bingye Han, School of Civil and Transportation Engineering, Beijing University Of Civil Engineering And Architecture

Effect of the thermal-oxidative aging on the road performance and noise reduction ability of polyurethane porous elastic road surface

Hongjin Liu, Yuchun Li, Mingzhi Sun, Southeast University

The Performance and Application Prospect of Polyurethane Modified Asphalt Reclaimed Pavement with 100% RAP

Bin Hong, Jianling Wang, and Dawei Wang, College of Future Technologies, Hohai University

Development and Typical Application of Polyurethane Based Paving Material

Shifa Xu, Zhanghui Li, School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture

Noise-Reducing Polyurethane Porous Elastic Mixture: Development, Water Stability, and Aging Resistance

Shuangyan Zhang 1, Bingye Han 2
1 School of Civil and Transportation Engineering, Beijing University Of Civil Engineering And Architecture, 102616 China, 2108230123008@stu.bucea.edu.cn
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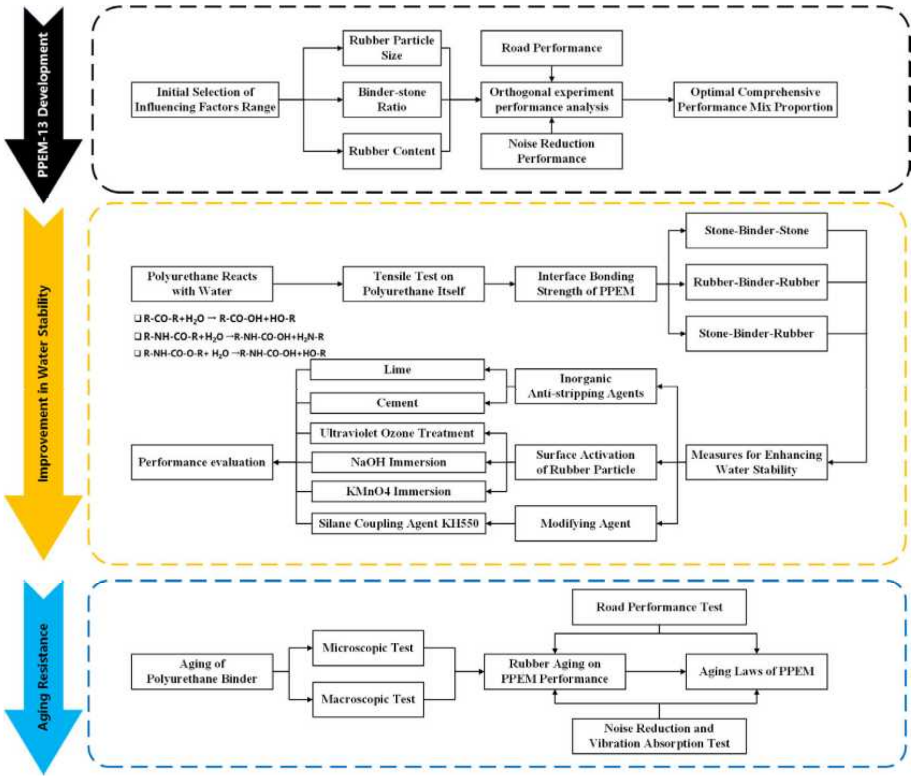
Graphical abstract



1 Objectives and Methodology

To address the current issue that noise-reducing pavements struggle to balance noise reduction performance and pavement performance, this study utilized a single-component polyurethane developed independently by the research group as the binder and incorporated rubber particles to develop Polyurethane Porous Elastic Mixture (PPEM) with an optimal mix proportion of PPEM-13, which takes into account both noise reduction and comprehensive pavement performance. Based on the macro and micro analysis results of water damage, the water stability of the mixture was improved, and the best water stability improvement plan was determined. Finally, the degradation laws of pavement performance and noise reduction performance of PPEM-13 under ultraviolet aging, thermal oxidation aging, and temperature-humidity aging were explored, and the durability of the mixture under aging was evaluated and analyzed.

2 Major results and findings

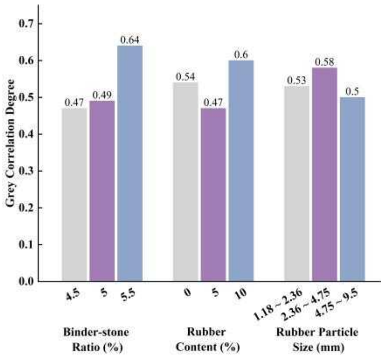
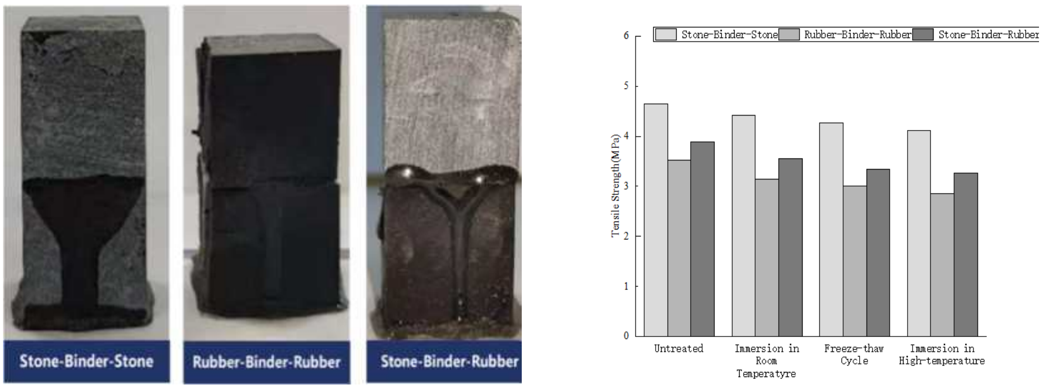


Figure 1 The average grey correlation degree of each factor

Table 1 PPEM-13 Performance Comparison

Indicator	PPEM-13	OGFC-13	AC-13
Dynamic Stability (times / mm)	29800	7369	96.7
Bending Strain (με)	18452	3154	2340
Immersion Mass Loss (%)	8.6	15.7	—
Immersion Marshall Stability (kN)	18.6	4.8	9.21
Noise (dB (A))	90.1	92.8	96.7



(a) Three interfaces in the mixture (b) Tensile strength test results

Figure 2 Strength test of the mixture interface

Table 2 Test results of water stability improvement measures

Indicator	Blank Group	0.5% Cement	Immersion in $KMnO_4$ Solution	2% KH550	Comprehensive Treatment
Dynamic Stability (times / mm)	29780	30115	29778	31156	32051
Bending Strain at Failure (με)	18451	17837	18923	19426	19064
Tire Drop Noise (dB (A))	90.1	91.0	89.9	90.1	90.6

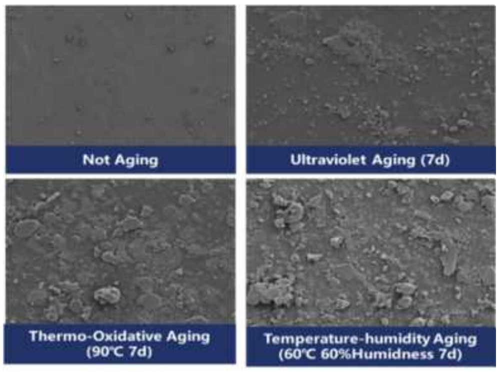


Figure 3 Microscopic morphological changes of polyurethane before and after aging

Effect of the thermal-oxidative aging on the road performance and noise reduction ability of polyurethane porous elastic road surface

Hongjin Liu [1, 2], Yuchun Li[2*], Mingzhi Sun[2]
[1] Southeast University, Nanjing, 100083 China
[2] Research Institute of Highway Ministry of Transport, Beijing, 100083 China, yc.li@rioh.cn

Graphical abstract (Provide a graphical abstract to summarize this presentation.)

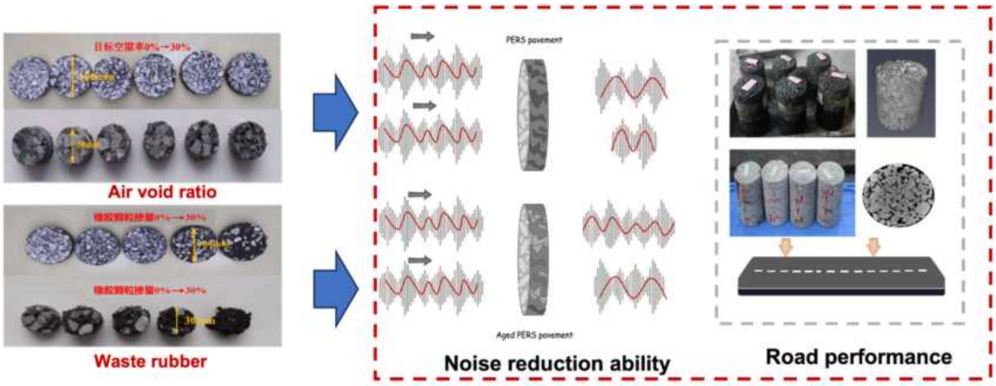


Figure 1 Graphical abstract

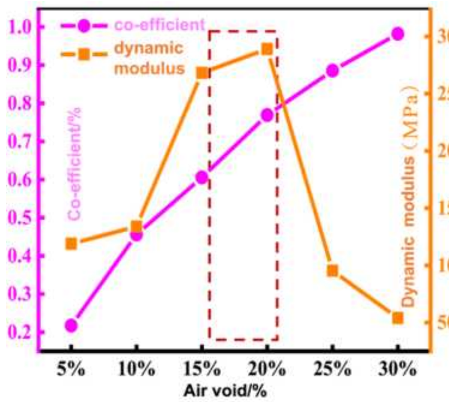
1 Objectives and Methodology

This work aims to reveal the mechanism of sound absorption and vibration reduction of PERS, optimize the road performance and noise reduction ability of PERS mixture by changing void ratio and content of waste rubber particles. The ability of sound absorption and vibration reduction were evaluated by the impedance tube test, tire vertical drop noise test and uniaxial compression dynamic modulus test.

In addition, the thermal-oxidative aging of waste rubbers under different aging times on the road performance and noise reduction ability of PERS mixtures was explored. In this work, the waste rubbers underwent thermal-oxidative aging for varying durations, after which they were compounded with PU adhesive and aggregates of different particle sizes to prepare both unaged/aged PERS mixtures.

2 Major results and findings

Introduce the major research results and findings with table and charts.



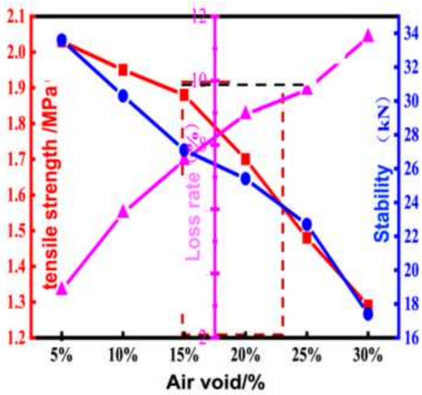


Figure 2. The influence of porosity and rubber particle dosage on noise reduction function and mechanical properties of PERS.

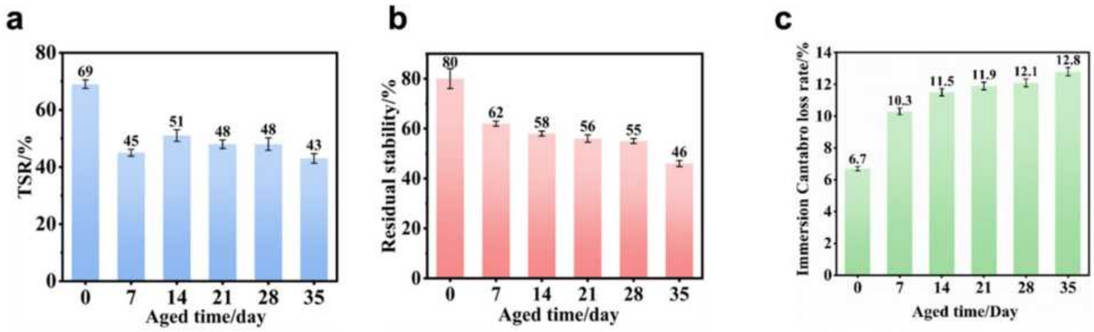


Figure 3. Results of TSR (a), the immersion Marshall residual stability (b) and immersion Cantabro loss rate (c) after different aging time for waste rubbers.

The Performance and Application Prospect of Polyurethane Modified Asphalt Reclaimed Pavement with 100% RAP

Bin Hong [1], Jianling Wang [2], and Dawei Wang [3]

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Graphical abstract

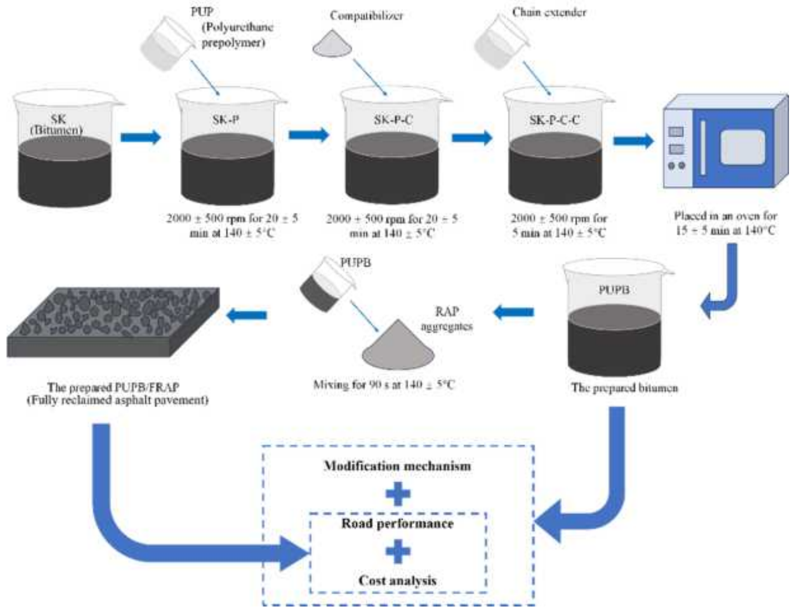


Figure 1 Graphical abstract

1 Objectives and Methodology

The recycling and reusing of reclaimed asphalt pavement (RAP) are generally restricted by the limited integration of RAP and the insufficient service life of recycled products. This research incorporated the polyurethane prepolymer (PUP) system into bitumen, creating an innovative bonding material to develop a fully reclaimed asphalt pavement (FRAP) mixture including 100% RAP. Firstly, the the PUP system modified bitumen (PUPB) binder was obtained by the orthogonal test. Then, the road performance and modification mechanism of the PUPB binder were analized by the gel permeation chromatography test, rheological property test, free-surface energy measurement, Fourier-Transform infrared spectroscopy (FT-IR) test and molecular dynamic simulation. The road performance of PUPB/FRAP mixture was furtherly investigated by the water stability test, dynamic stability test and low-temperature flexural properties test. Lastly, the cost of both PUPB and its mixture was analyzed compared with epoxy asphalt binder and its FRAP mixture by comparing the 200-meter test road.

2 Major results and findings

Introduce the major research results and findings with table and charts.

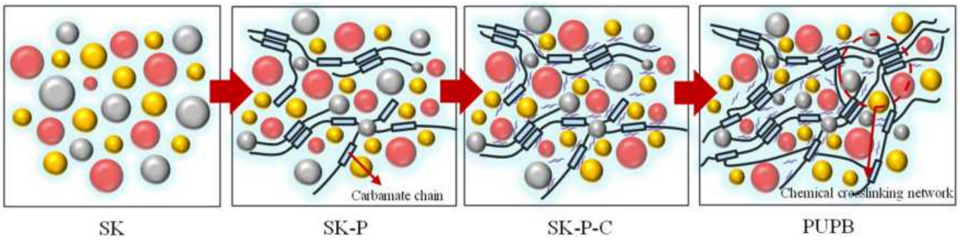
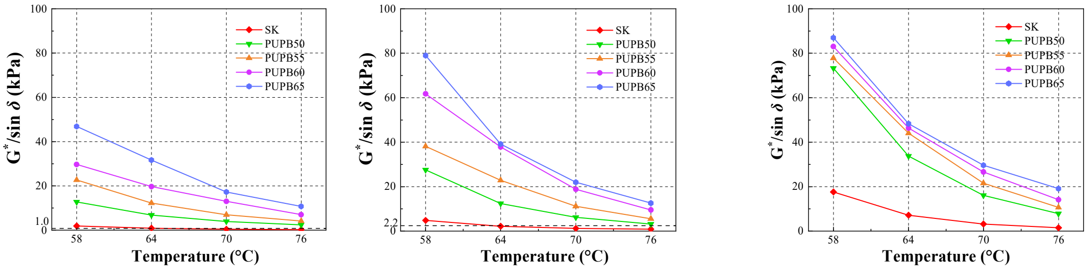
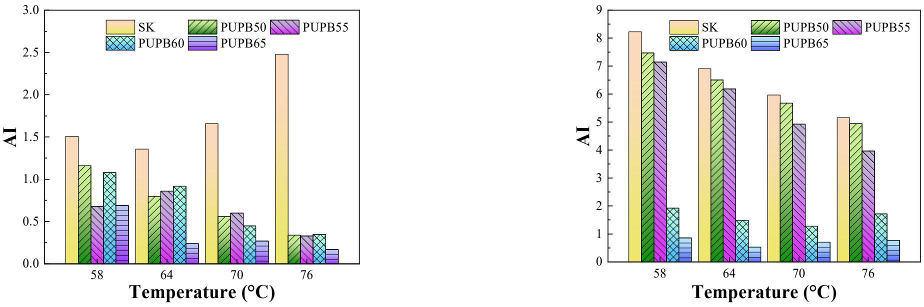


Fig. 1 Schematic diagram of the PUPB microstructure formed by PUP system modification effect



(a) (b) (c)

Fig. 2 Effect of the PUP system on rutting factors ($G^*/\sin\delta$) of (a) unaged samples; (b) TFOT-aged samples; (c) PAV-aged samples

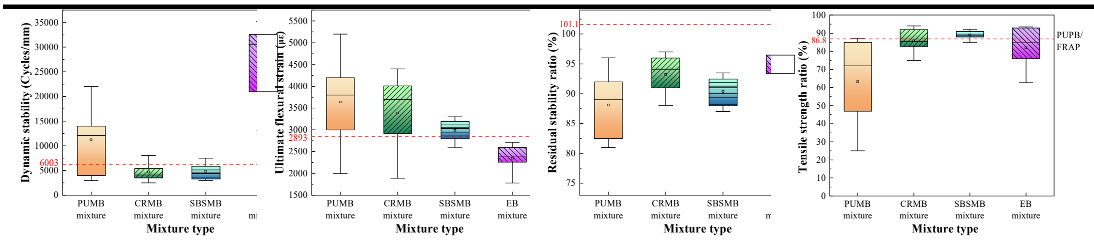


(a) (b)

Fig. 3 Aging indexes of (a) TFOT-aged samples; (b) PAV-aged samples

Table 1 Road performance results of PUPB/FRAP mixture

Indices	Bitumen-aggregate ratio/%	Void content/%	Dynamic stability/(Cycles/mm)	Ultimate flexural strain/με	Residual stability ratio/%	Tensile strength ratio/%
Values	1.9	4.9 ± 0.3	6003 ± 183	2893 ± 556	101.1	86.8
Requirement	—	—	≥2800	≥2500	≥85	≥80



(a) (b) (c) (d)

Fig. 4 Road performance results of PUMB, CRMB, SBSMB, and EB mixtures

Development and Typical Application of Polyurethane Based Paving Material

Shifa Xu [1] and Zhanghui Li [1]

[1] School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, 100044 China, Xushifa@bucea.edu.cn; 1108140024065@stu.bucea.edu.cn

Graphical abstract

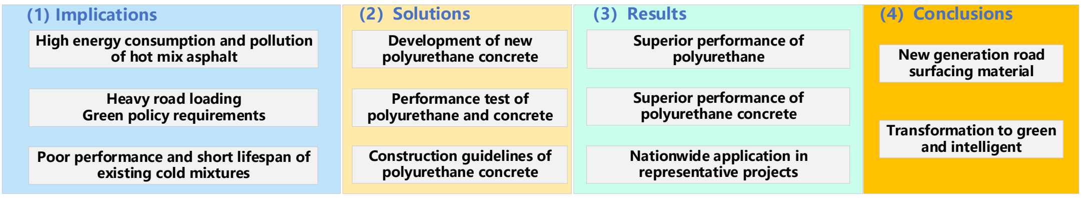


Figure 1 Graphical abstract

1 Objectives and Methodology

At present, China ranks first in the world in terms of expressway mileage. Traditional hot mix asphalt mixtures are limited by high energy consumption, heavy pollution, and large amounts of waste. Therefore, further optimization of pavement materials are of great significance to the ecological environment. Our team developed a new type of polyether polyurethane, and experiments verified the performance of polyurethane is far superior to that of virgin asphalt and modified asphalt. In addition, we also developed a penetration resistance tester, established a real-time compaction prediction model, and compiled construction guidelines for polyurethane concrete, which improved the workability of polyurethane concrete construction and shortened the traffic opening time.

2 Major results and findings

Introduce the major research results and findings with table and charts.

Experiment results confirmed the performance of polyurethane meet requirements and significantly surpass virgin asphalt (as shown in Table 1); Fatigue performance and service life of polyurethane concrete are superior than SMA and SBS asphalt mixtures (as shown in Table 2); Key indicators and application of polyurethane in waterproof bonding layer are detailed in Table 3 and Figure 2.

Table 1 Polyurethane technical requirements

Performance	Test results	Technical requirements
Viscosity (25℃, mPa·S)	1863	≤2500
Tensile strength(MPa)	8.6	≥5
Elongation at break(%)	378	≥300
Low temperature bending	No cracks	No cracks
Bonding strength with steel interface(MPa)	3.9	≥2.5

Table 2 Polyurethane concrete technical requirements

Performance	Polyurethane concrete	SMA mixture	Epoxy asphalt mixture
Dynamic stability (70℃, 1.0MPa, frequency/mm)	58000	4800	12600

Low temperature bending strain（-10℃, με）	15415	3764	3980
Freeze-thaw split residual strength（MPa)	＞1.0	0.4	0.6

Table 3 Waterproofing adhesive layer

Adhesive layer type	Epoxy asphalt	SBS modified asphalt	Polymer waterproofing adhesive layer
Slant shear strength (25℃, MPa)	0.56	0.48	3.6
Tensile strength (25℃, MPa)	0.61	0.57	1.7

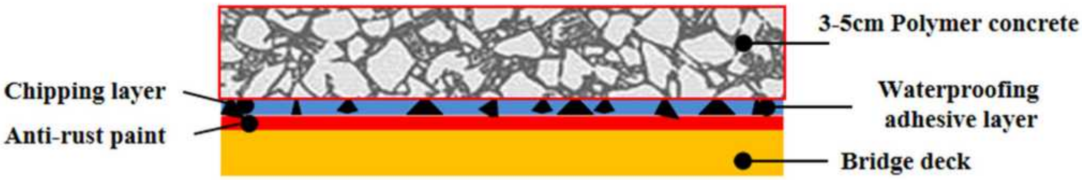


Figure 2. Application of polyurethane in waterproof bonding layer

Parallel Session H2

Topic: Challenges of Multi-physics Service Environments on Asphalt Pavement

Chair: Wentao Wang, Assistant Professor, University of Science and Technology Beijing Cochair: Kang Zhao, Assistant Professor, Liaoning University of Technology

Speech:

Functional Degradation Prevention of Pavement in Extreme Conditions—Engineering Practices of Cold Paving Technology

Xing Peng, CCCC Infrastructure Maintenance Group Co., Ltd., Beijing

基于精细剥离筛分的再生技术应用摘要

樊向阳

Demonstration Project of Comprehensive Application of Recycled Solid Waste Materials in the Whole Structural Layers of the Road

JianFeng Li

Complete Technology for Natural Aging Mechanism and Durability Improvement of Asphalt Pavement in Typical Climatic Regions of Northwest China

Shanglin Song, Xiaoming Kou, Fukui Zhang, Hongbin Chen, Haihong Zhang, Gansu Provincial Highway Development Group Co., Ltd

Effects of Fine RAP Content and Mixing Procedure on Recycled Asphalt Mixture

Sudi Wang, Jian Xu, Jie Wang, Research Institute of Highway Ministry of Transport

Influence of Service Environment Concerning Dynamic Water Pressure on Asphalt Pavement

Wentao Wang

Functional Degradation Prevention of Pavement in Extreme Conditions—Engineering Practices of Cold Paving Technology

Xing Peng
CCCC Infrastructure Maintenance Group Co., Ltd., Beijing, 100088 China,
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In large temperature difference regions, the crack resistance of asphalt concrete pavements is severely challenged by extreme climatic conditions, particularly the universality and severity of crack diseases. Asphalt pavement crack diseases are prevalent in regions such as Xinjiang and Tibet. As the main environmental factor under extreme climatic conditions, freeze-thaw cycles significantly affect the crack resistance of asphalt mixtures. However, existing studies have mostly focused on the impact of freeze-thaw cycles themselves, with less attention paid to the role of water during freeze-thaw processes. Therefore, this study aims to evaluate the impact of water-mediated freeze-thaw cycles on the crack resistance of asphalt concrete in large temperature difference regions and explore the mechanism of water in this process.

To achieve this goal, the authors designed freeze-thaw tests (with/without water) for asphalt mixtures simulating the freeze-thaw environment in large temperature difference regions. The test specimens were prepared using 70# base asphalt and basalt aggregates, compacted by rotary compaction in accordance with AASHTO T312, and cut into pre-notched semicircular specimens. The temperature range was set from -25℃ to 25℃, with each cycle lasting 8 hours. The semi-circular bending (SCB) test was used to evaluate the fracture energy (Gf), crack resistance index (CRI), and fracture toughness index (FTI) of the specimens. A three-parameter exponential decay model was employed to fit the test data, and analysis of variance (ANOVA) was used to test the effect of the water environment on the crack resistance of asphalt mixtures.

The results revealed that water-mediated freeze-thaw cycles significantly reduced the crack resistance of asphalt mixtures, with the fracture toughness index decreasing most significantly by 47.4%. The three-parameter exponential decay model successfully fitted the variation trend of crack resistance indices with the number of freeze-thaw cycles, showing characteristics of rapid initial decay, slowed decay rate in the middle stage, and stabilization in the later stage. ANOVA results confirmed the significant impact of the water environment on the crack resistance of asphalt mixtures. Water accelerated the performance degradation of asphalt mixtures during freeze-thaw cycles; especially in the water environment, freeze-thaw cycles had a more significant impact on the stiffness of asphalt mixtures. This phenomenon may be related to the infiltration and expansion of water during freeze-thaw processes, leading to intensified internal structural damage of asphalt mixtures. Based on these findings, it is recommended that in the design and maintenance of roads in large temperature difference regions, full consideration should be given to the impact of water on the performance of asphalt mixtures, and corresponding waterproofing and drainage measures should be adopted. Additionally, the study suggests further exploration of materials and design methods to improve the crack resistance of asphalt mixtures to adapt to extreme climatic conditions.

This study not only provides a new scientific basis for the design and maintenance of asphalt pavements in large temperature difference regions but also has important practical value for improving road durability and reducing maintenance costs. By deeply understanding the role of water in freeze-thaw cycles, we can better predict and control crack diseases in asphalt pavements, thereby extending their service life.1 Objectives and Methodology

1.1 Fracture energy

Fracture energy is the energy consumed per unit area for crack propagation per unit length. A larger fracture energy indicates stronger low-temperature crack resistance of asphalt concrete at a certain temperature. However, some studies have shown that fracture energy, as a single fracture index, cannot fully reflect the cracking behavior of asphalt concrete [17-18]. The calculation method of fracture energy is shown in Equation (1):

$$G_f = \frac{W_f}{A_{lig}} \quad (1)$$

Where: Wf is the fracture work (J); Alig is the ligament area (m^2), and Alig =(r−a)×t.

1.2 Crack resistance index

KASEER et al. proposed an index for evaluating the low-temperature performance of asphalt mixtures based on fracture energy, namely the Crack Resistance Index (CRI). Its calculation formula is shown in Equation (2):

$$CRI = \frac{G_f}{|P_{max}|} \quad (2)$$

This index uses the ratio of fracture energy to peak load as the evaluation index for asphalt mixture crack resistance, with the unit of mm. It can be approximately regarded as the effective cracking distance of the material. This index can distinguish asphalt concretes with similar fracture energies but different peak loads, reflecting the brittleness of the material (for materials with the same fracture energy, the larger the peak load, the smaller the CRI, and the more "brittle" the material).

1.3 Fracture toughness index

Kim et al. used the Flexibility Index (FI) to evaluate the crack resistance of asphalt concrete, with the calculation formula shown in Equation (3):

$$FI = \frac{G_f}{|m|} \quad (3)$$

The ratio of fracture energy to the slope (m) at the inflection point of the post-peak load-displacement curve is used to reflect the crack propagation rate of asphalt concrete, which can be used to identify early brittle cracking of asphalt concrete. However, due to the difficulty in fitting the post-peak curve to determine its inflection point, and the large variability of the inflection point slope m, especially in low-temperature environments, the evaluation of the low-temperature performance of asphalt mixtures using the flexibility index is unstable and inaccurate. On the basis of the flexibility index, the authors used the approximate slope value at the point where the peak force decays to 75% instead of the slope at the inflection point of the post-peak curve, corrected the specimen size, and considered the cracking displacement, thus proposing a Fracture Toughness Index (FTI) to better evaluate the fracture toughness of asphalt mixtures, as shown in Equation (4):

$$FTI = \frac{t}{50} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{r-a}\right) \quad (4)$$

In Equation (4): FTI is the fracture toughness index (dimensionless); t is the thickness of the semicircular specimen (mm); as shown in Figure 4, m75 is the approximate slope value at the point where the peak force decays to 75% in the load-displacement curve, calculated by Equation (5); l75 is the displacement value at the point where the peak force decays to 75% (mm); r is the radius of the specimen; a is the notch length (m).

$$m_{75} = \frac{P_{80}-P_{70}}{l_{80}-l_{70}} \quad \textbf{(5)}$$

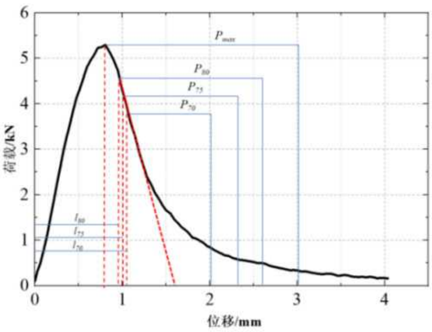
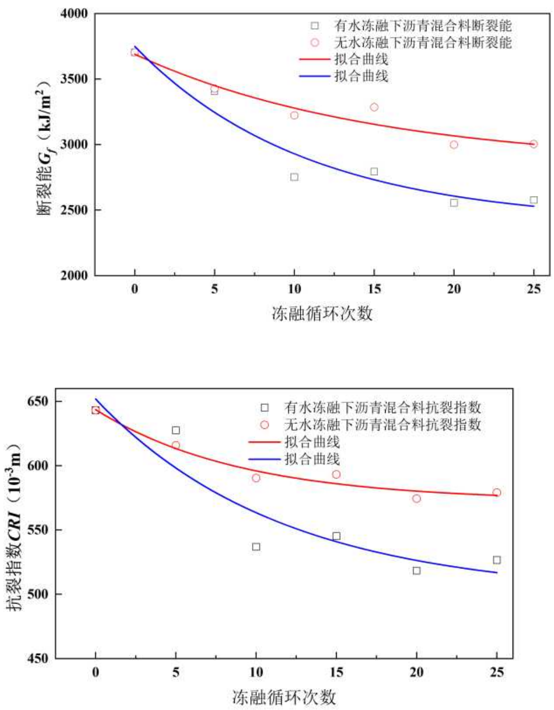
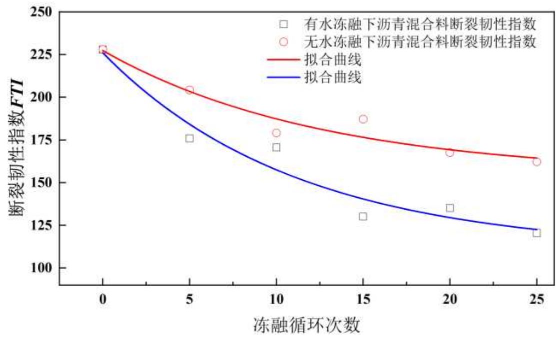


Figure 1 Schematic diagram of load-displacement curve



(a) Fitting results of fracture energy (b) Fitting results of crack resistance index



(c) Fitting results of fracture toughness index

2 Major results and findings

2.1 High-performance waterborne-epoxy-asphalt pavement

This technology addresses pavement scouring caused by rainwater pumping and vehicle loading. Its unique chemical structure (combining rigid bisphenol A groups from epoxy resin and flexible ether bonds from asphalt) enhances bonding performance: Reduced shedding rate: With aqueous epoxy content increasing from 0% to 7%, the asphalt shedding rate under scouring decreased by 34% (Table 1), significantly reducing material loss in extreme rainfall conditions. Enhanced bonding contact: The contact ratio between epoxy structures and aggregates increased by 50% (Table 1), forming a tighter interface. Pull tests showed its drawing strength (0.92 MPa) was 3 times that of traditional asphalt (0.31 MPa).

Table 1 Performance of waterborne-epoxy-asphalt with different epoxy contents

Aqueous epoxy content (%)	Shedding rate	Contact ratio with aggregates
0	0.61	-
3	0.53	4.09
7	0.27	9.24

2.2 High-performance room-temperature liquid asphalt

This technology solves the low strength issue of traditional cold mixes by integrating base asphalt, bio-based materials, and reactive powder: Rapid strength development: Marshall stability reached 4.97 kN in 30 minutes and 19.28 kN after immersion (Figure 2a), far exceeding traditional cold mixes. Excellent rutting resistance: 7-day rutting test value exceeded 6000, over 20 times that of conventional cold repairs (Figure 2b), ensuring durability under heavy traffic.

3. Analysis of Fitting Results

The fitting results showed that the exponential model could well reflect the changes in the crack resistance of the mixture with freeze-thaw cycles. The adjusted R2 of each index ranged from 0.796 to 0.936. ANOVA was used to test the significance of the exponential model fitting, with a confidence level of 95% (α=0.05). When the p-value was less than 0.05, the curve fitting was statistically significant. The fitting results showed that all indices met the condition of p-value < 0.05, indicating that the three-parameter exponential decay model was consistent with the variation trend of the test data, i.e., there was a good correlation between the test data and the regression equation. Figures 2 (a), (b), and (c) show the fitting curves of the relationships between fracture energy, crack resistance index, fracture toughness index, and the number of freeze-thaw cycles, respectively. It can be clearly found that both the fracture energy and fracture toughness index of asphalt mixtures showed a rapid early decrease, and with the increase in the number of freeze-thaw cycles, the decay of fracture energy and fracture toughness gradually stabilized. During the early freeze-thaw cycles, the crack resistance evaluation indices of asphalt mixtures decayed rapidly; with the increase in the number of freeze-thaw cycles, the decay rate became soother, reflecting that the initial freeze-thaw cycles had a greater impact on the low-temperature crack resistance of asphalt mixtures, which was consistent with the severe early damage phenomenon of asphalt pavements in large temperature difference regions.

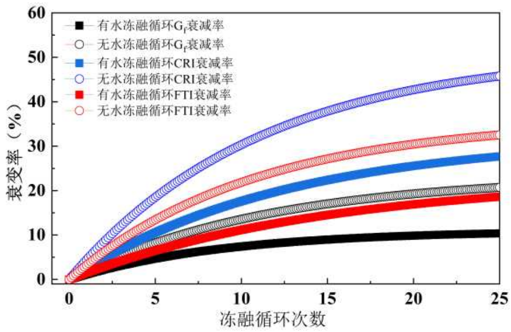


Figure 3 Relationship between decay rate of crack resistance indices and number of freeze-thaw cycles

The loss rate model was used to evaluate the decay trend of the crack resistance of the mixture under freeze-thaw cycles. The model is as follows:

$$P(t) = 1 - \frac{f(t)}{f(0)}(1)$$

Where: P(t) is the dimensionless loss parameter of each crack resistance index; f(0) is the initial crack resistance of the asphalt mixture; f(t) is the crack resistance of the asphalt mixture after t freeze-thaw cycles; in this model, t ranges from 0 to 25, which is consistent with the actual number of freeze-thaw cycle tests.

As shown in Figure 3, under the same number of freeze-thaw cycles, the low-temperature crack resistance indices of asphalt mixtures after freeze-thaw in the water environment decayed more significantly. After 25 freeze-thaw cycles in the water environment, the fracture energy (Gf), crack resistance index (CRI), and fracture toughness index (FTI) decayed by 30.4%, 18.1%, and 47.4%, respectively, while in the water-free environment, they decayed by 18.9%, 10.0%, and 27.2%, respectively. Repeated freeze-thaw cycles reduced the bonding force between asphalt and aggregates and caused damage to the internal structure of asphalt mixtures. Meanwhile, after water entered the interior of asphalt mixtures through cracks and voids, the erosion and thawing expansion of water intensified this process. The test analysis showed that water had a significant impact on the crack resistance of asphalt mixtures after freeze-thaw cycles; the decay rate of the crack resistance of asphalt mixtures under freeze-thaw cycles in the water environment was significantly higher than that in the water-free environment.

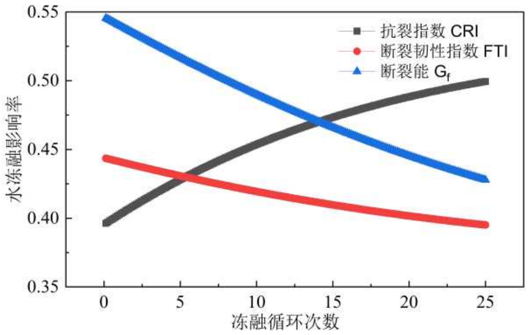


Figure 4 Relationship between the impact rate of water-mediated freeze-thaw cycles and the number of freeze-thaw cycles

The impact rate L(x) of water-mediated freeze-thaw cycles was calculated to objectively compare the decay of crack resistance indices of asphalt mixtures during water-free and water-mediated freeze-thaw cycles, and to analyze the impact of water-mediated freeze-thaw cycles on the crack resistance indices of asphalt mixtures.

$$L(t) = \frac{P(t)_{有水} - P(t)_{无水}}{P(t)_{有水}} \quad \textbf{(2)}$$

Where: L(t) is the impact rate of water-mediated freeze-thaw cycles on the crack resistance indices of asphalt mixtures; a larger L(t) indicates a more significant impact of water-mediated freeze-thaw cycles on the crack resistance of asphalt mixtures; P(t) water is the decay rate of crack resistance indices under water-mediated freeze-thaw cycles; P(t) water-free is the decay rate of crack resistance indices under water-free freeze-thaw cycles.

As shown in Figure 4, the water-mediated freeze-thaw impact rates of fracture toughness index and fracture energy were positively correlated with the number of freeze-thaw cycles, while the water-mediated freeze-thaw impact rate of crack resistance index was negatively correlated with the number of freeze-thaw cycles. Analysis of the intersection points of each curve in the figure showed that: when the number of water-mediated freeze-thaw cycles t was between 0 and 5, the impact of water-mediated freeze-thaw cycles on the crack resistance indices was the smallest; when t>5, the impact on the fracture toughness index was the smallest; when t was between 0 and 14, the impact on the crack resistance indices was the largest; when t>14, the impact on the crack resistance index was the largest. Fracture energy characterizes the low-temperature crack resistance of asphalt mixtures, while fracture toughness index and crack resistance index can reflect the "toughness" and "brittleness" of asphalt mixtures at low temperatures, respectively. Therefore, with the increase in the number of freeze-thaw cycles, the impact of water on the "brittleness" of asphalt mixtures gradually increased, while its impact on the "toughness" gradually decreased.

4.Engineering application effects

G0121 highway (waterborne-epoxy-asphalt): At 76℃, the complex shear modulus increased by 42% compared to traditional asphalt, with phase angle decreasing by 8%, indicating improved high-temperature rutting resistance. Wet track abrasion value and the value of Cantabro Test decreased by 53% and 39% respectively, verifying anti-degradation performance.Cold in-place recycling (S311 road): Recycled 200 million tons of RAP annually, reducing CO_2 emissions by 223 million tons (per IPCC 2021 data). The technology lowered construction costs by 30% and achieved a splitting strength ratio of 81.6% (exceeding the 70% standard), meeting durability requirements.

基于精细剥离筛分的再生技术应用摘要

Xiangyang Fan
Jiangxi Communications Investment Maintenance Technology Group Co., Ltd

本汇报围绕基于精细剥离筛分的沥青路面再生技术展开，在“双碳”目标及《交通强国建设纲要》等政策推动下，针对江西省高速公路总里程 6700 多公里中 50%以上路龄超 10 年、每年产生数百万吨 RAP 却面临传统处理“三低”（掺量≤30%、层位低、利用率低）的问题，重点介绍了精细剥离筛分核心技术，该技术通过省内首台设备采用立轴式冲击破实现“油石分离”，经多级振动筛将 RAP 分为 3-5 档规格骨料，大幅降低沥青含量变异、级配波动及假粒径含量，使粗料表面油膜厚度≤100μm、结团率降低 18-37%、4.75mm 以上粗料变异系数下降 55%以上；在厂拌热再生应用中，基于该技术突破传统掺量限制，成功验证 55%、70%掺量 AC-20 等再生混合料，性能指标满足设计规范要求，其中 70%掺量动稳定度达 11455 次/mm，2023 年 11 月铺筑 3km55%掺量试验段、2024 年 9 月铺筑 500m70%掺量试验段后大规模应用，70%掺量 AC-20 混合料单价降低 41.4 元/t、成本降幅约 13.7%，每吨结余 RAP 料折合 11.3 元；同时，基于精细剥离筛分的 RAP 形成多元化应用，包括 100%RAP 掺量再生冷补料已自产自销并入驻政府采购平台，ECA 超薄罩面动稳定度＞6000 次/mm 适用于重载交通，70%掺量高模量再生混合料在 G70 福银高速应用、动态模量达 7766MPa（45℃），50%RAP 掺量应力吸收层在抚州段应用表现优异，100%掺量再生微表处通过添加乳化再生剂使 6d 湿轮磨耗值降低 20%接近新料性能；综上，该技术实现了 RAP 从“废料”到“资源”的转变，为交通领域“双碳”目标及资源循环经济发展提供了可推广的技术方案。

Demonstration Project of Comprehensive Application of Recycled Solid Waste Materials in the Whole Structural Layers of the Road

Jianfeng Li,

Shanxi Road & Bridge Group Test and Detection Center Co., Ltd

1. Project Feature

The project features can be summarized as "four more and one less", that is, the farmlands along the line are more, the soft ground sections are more, the shallow buried pipelines are more, the solid waste materials along the line are more, and the filling soil resources along the line is less.

2. Project Scale

Large volume of subgrade engineering workload: with 3,212,000 cubic meters of embankment fillings, 247,000 cubic meters of subgrade, 234,000 cubic meters of soft foundation riprap, and 320,000 cubic meters of stone slag cushion, the project scale is significant.

Large quantity of concrete engineering workload: the quantity of concrete engineering workload like culvert, bridge, retaining walls, etc. is large, such as 60,600 cubic meters of culvert concrete, 21,800 cubic meters of the bridge upper concrete, the construction task is heavy..

3. Measures for Comprehensive Application of Recycled Solid Waste Materials

(1) Soft foundation treatment: Limestone tailings as crushed stone for squeezing silt and stone slag cushion layer in soft foundation disposal.

(2) Subgrade Filling: CFB ash and coal gangue are selected as subgrade filling materials.

(3) Cushion Layer: Crushed and screened tailings mixture is selected as the cushion material.

(4) The sub-base and base layer: eco-cement is selected to replace traditional cement, and coal gangue is selected to replace partial crushed stone coarse aggregate.

(5) Surface Course: High-performance desulfurized rubber powder composite modified asphalt.

(6) Bridges and Culverts: Granulated blast furnace slag powder and fly ash, high-performance admixtures are used as concrete mixing materials.

(7) Temporary construction: CFB ash and coal gangue can be used to make building blocks, fly ash can be used in masonry mortar and plastering mortar, tailings can be processed into lightweight panels, and high-performance admixtures can be used as concrete admixtures and cement admixtures for temporary construction facilities.

(8) Ecological Components: Curbs, roadside stones, hexagonal bricks, grass-planting bricks and other ecological component products are used in road edges, slopes, parking lots, sidewalks, green belts and other places.

(9) High-performance Admixtures: Used as concrete admixtures, cement grouting admixtures, etc.

(10) Ecological cement: Used in highway subbase, base course, subgrade improved soil and other projects.

(11) Magnesium-based sound barrier: Applied in highway noise mitigation

projects.

4. Economic Analysis

Through the calculation and comparison of the price of Recycled solid waste materials and the materials being replaced, the project has saved more than 20,000,000 yuan in total cost.

Complete Technology for Natural Aging Mechanism and Durability Improvement of Asphalt Pavement in Typical Climatic Regions of Northwest China[1]

Shanglin Song[1,2*], Xiaoming Kou[1], Fukui Zhang[1], Hongbin Chen[3], Haihong Zhang[3]

(1. Gansu Provincial Highway Development Group Co., Ltd; 2. School of Civil Engineering and Hydraulic Engineering, Tsinghua University;3. Gansu Provincial Transportation Research Institute Group Co., Ltd)

The aging behavior of asphalt pavement during long-term service is influenced by various environmental factors, including ultraviolet (UV) radiation, temperature, and moisture. Each of these factors contributes to the gradual deterioration of asphalt in different ways. UV radiation, for instance, can break down the molecular chains in asphalt, fragmenting large molecules into smaller ones, which subsequently recombine into larger structures. This process leads to changes in the asphalt's physical properties, such as reduced flexibility, increased brittleness, and elevated softening points. At the same time, oxygen in the air reacts with the double bonds in asphalt molecules, forming oxidation products that further harden the material, darken its color, and diminish its adhesive and plastic properties. Prolonged exposure to high temperatures accelerates these processes by inducing thermal decomposition and polymerization reactions, generating harmful substances that exacerbate the aging of the asphalt. In moist environments, water infiltrates the surface of the asphalt, softening it and lowering its resistance to aging. However, current laboratory simulations fall short of fully replicating the complex aging behavior of asphalt under real-world service conditions.

This study employs a range of experimental methods, including Nuclear Magnetic Resonance (NMR), Gel Permeation Chromatography (GPC), Fourier Transform Infrared Spectroscopy (FTIR), elemental analysis, and four-component analysis, to assess the chemical changes in asphalt of nature aging. By examining the aging behavior of asphalt under three distinct aging modes, three different asphalt film thicknesses, and across five representative climatic regions over various time periods to study the natural aging mechanisms of asphalt in the Northwest region. Grey Relational Analysis (GRA) is applied to establishes correlations between natural aging conditions and the microscopic properties of asphalt, shedding light on the influence of key environmental factors on asphalt aging in the region's complex climate.

The research found that aging caused significant increases in both the carbonyl and sulfone indices for both base and SBS-modified asphalt, with all-weather aging having the most pronounced effect. As natural aging time and asphalt thickness increased, the sulfone index and functional group index (the sum of carbonyl and sulfone indices) showed a positive correlation. However, the carbonyl index exhibited no noticeable changes. The thickness of the asphalt film was found to play a crucial role in aging sensitivity, with thicker asphalt showing a limited depth of oxidation penetration.

The study also observed that aging significantly increased the oxygen content in

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the asphalt, indicating the formation of more oxygen-containing functional groups. SBS-modified asphalt demonstrated some resistance to oxidation compared to the base asphalt. The oxygen content followed a specific order of impact: thermal oxidation + UV aging, followed by all-weather aging, and thermal aging, suggesting a strong correlation between oxidation reactions and light exposure. Moreover, the exposure of all-weather aged samples to air caused a decrease in dust accumulation, which reduced their contact with light and oxygen, thereby slowing down the rate of molecular changes.

When examining molecular structure, the study found that after aging, the number-average molecular weight of base asphalt increased, whereas SBS-modified asphalt showed a slight decrease, likely due to the degradation of SBS molecular structures. This result aligned with Nuclear Magnetic Resonance (NMR) findings, which indicated that aging caused an increase in the number and length of aromatic ring structures in base asphalt, while SBS molecular chains fractured.

The research also explored the composition changes during aging, noting that some light components such as saturates and aromatics volatilized, while others oxidized into heavier components such as asphaltenes and resins. These changes were not entirely linear; the extent of the increase in asphaltenes and resins and the decrease in saturates and aromatics varied. Additionally, the study found that asphalt layers with increased thickness exhibited less aging, with the 1.0 mm thickness showing the most severe aging.

To assess the effect of climatic environments, the study compared the aging behavior of asphalt in five different cities across various climate zones. It was found that the impact of climate on aging was most significant in Longnan's warm climate zone, followed by colder zones such as Hexi and the Plateau. The results also indicated that while the elemental composition of base asphalt was mainly influenced by aging time and film thickness, SBS-modified asphalt was more sensitive to temperature and aging time, with humidity having a minimal effect on both.

Overall, these findings provide valuable insights into the aging processes of asphalt under various environmental conditions, offering a deeper understanding that can be used to improve the durability and performance of asphalt materials.

Effects of Fine RAP Content and Mixing Procedure on Recycled Asphalt Mixture

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Graphical abstract

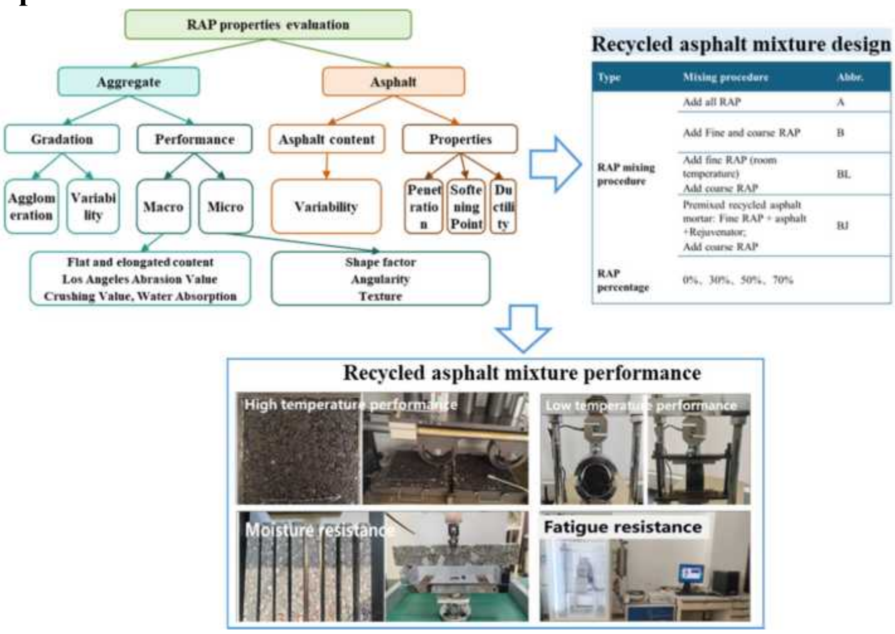

Figure 1 Graphical abstract

1 Objectives and Methodology

Recycled asphalt pavement technology has basically become the highway reconstruction and expansion works and repair and maintenance projects' essential option. To enhance the application of reclaimed asphalt pavement (RAP), this study examined RAP utilization and the performance of recycled asphalt mixtures with high RAP content by refined separation techniques. Based on the RAP refined separation, the design method of hot central plant recycled asphalt mixture was studied, and the utilizable characteristics of RAP material after fine separation were analyzed. Three kinds of RAP addition methods were proposed. By the test of high-temperature rutting performance, water stability, low-temperature crack resistance and fatigue performance of recycled asphalt mixtures under different working conditions, the effects of different addition methods and addition ratios on the road performance of recycled asphalt mixtures were investigated.

2 Major results and findings

The major findings are concluded that the refined separation technology can not only effectively improve the addition proportion of RAP, but also effectively improve the pavement performance of recycled asphalt mixture. It was found that refined separation technology can increase the fine RAP content by 21.5%. It is proposed that the recycled asphalt mixtures produced by mixing RAP fines into recycled asphalt mortar in a pre-preparation manner have relatively better comprehensive performance, which can effectively solve the problem of utilizing oil-rich fine RAP. With the increase in the content of RAP, the high-temperature performance of the recycled asphalt mixture gradually improves, while its moisture stability slightly decreases. When the RAP contents are 30%, 50%, and 70%, the dynamic stability of the recycled asphalt mixture increases by 36%, 92%, and 121%, respectively, relative to the virgin asphalt mixture. Even at a 70% fractionated processed RAP content, the retained Marshall stability after water immersion and the freeze-thaw splitting strength ratio still satisfy the requirements of the general specifications.

Influence of Service Environment Concerning Dynamic Water Pressure on Asphalt Pavement

Wentao Wang
University of Science and Technology Beijing

When a vehicle drives on asphalt pavement with surface runoff, a dynamic environment of pore water pressure will be formed as water flow is continually driven by tires. The dynamic water environment not only aggravates the adverse stress state of dynamic structural response but also erodes asphalt materials, which finally causes the distress of moisture damage and decreases both the service quality and life of entire asphalt pavement. It is gradually realized that dynamic water environment tends to induce severe damage on asphalt pavement, but the existing research is still not sufficient. This study systematically discussed the damage of dynamic pore water pressure on asphalt pavement using various methods, such as numerical simulation, full-scale accelerated loading test and multi-scale lab tests. Dynamic response of pavement structure in dry and saturated conditions were compared, and so did the impact of factors such as pore water pressure magnitude, water temperature and conditioning duration on asphalt materials' service performance. Further, relevant mechanism of damage induced by dynamic water environment on asphalt materials was analyzed at multiple scales.

Dynamic Hydraulic scouring induced by a moving vehicle

The main conclusions are drawn as follows:

(1) The tire tracks can be precisely controlled in the full-scale accelerated loading test system. Dynamic response of asphalt pavement in saturated condition showed stronger indicators than that in dry condition. Pore water pressure was more sensitive to vehicle speed than vehicle load. A prediction model of dynamic pore water pressure was proposed based on the full-scale accelerated loading tests.

(2) Dynamic pore water pressure environment degrades the performance of asphalt materials, while the erosion ability of which is often between the static water immersion and freeze-thaw, and sometimes even more strict than the former. The moisture sensitivity of the mastic component inside asphalt mixture, which is often called fine aggregate mixture (FAM), greatly affected the resistance to moisture damage induced by dynamic water environment for the entire asphalt mixture.

Parallel Session I1

Topic: Next-Generation Resilient Airport Infrastructure: Key Technologies and Future Outlook

Chair: Jianming Ling, Professor, Tongji University

Speech:

Technology for Enhancing Durability and Airworthiness of Airport Runways in Harsh Conditions

Jianming Ling, Professor, Tongji University

To Be Available

Xinyan Ma, Senior Engineer, Civil Aviation Administration of China Research Base

Construction of a Full-Scale Accelerated Loading Test Platform for Civil Aviation Airport Pavements

Lin Qi, Professor, Civil Aviation University of China

Technological Innovation Facilitating Airport Operation Safety Assurance

Yubin Xu, Director, China Academy of Civil Aviation Science and Technology

Parallel Session I2

Topic: Smart Low-Altitude Transportation Systems: Development Pathways and Frontier Innovations

Speech:

Development of Intelligent Civil Aviation in the New Generation AI Era
Yi Liu, Professor, Civil Aviation Management Institute of China

Innovative Development of Air Transport and Low-Altitude Economy Research
Yu Tian, Professor, Tongji University

Challenges and Countermeasure Technologies for Low-Altitude Flight Operations
Xianlong Tan, Professor, The Second Research Institute of Civil Aviation Administration of China

Research and Judgment on Low-Altitude Economy from the Perspective of the Three - Dimensional Analysis Model
Zhiqin Huo, Research Fellow, Hangzhou Innovation Institute of Beihang University

Parallel Session J1

Topic: Highway Geotehnical Engineering Theory and Technology

Chair: Sheqiang Cui, Professor, Shandong University

Introduction:

Highway geotechnical engineering applies the principles of soil mechanics and rock mechanics to the design and construction of roads and highways. It involves understanding the behavior of soil and rock under various conditions to ensure the stability and safety of road structures. Geotechnical engineers use these principles to analyze the strength and behavior of soil and rock, which are essential for designing stable road foundations, slopes, and other structures. For an instance, the design of the embankment is informed by geotechnical investigations and analysis to ensure the subgrade soils can withstand traffic loads and environmental conditions (e.g., temperature and moisture variations). Moreover, assessing the stability of slopes along the highway alignment is also critical. Geotechnical engineers use various methods to analyze slope stability and design appropriate stabilization measures, such as earthen cover system. Geotechnical operations are of importance with respect to soil sampling, investigating geomaterials properties, controlling groundwater level and flow as well as environmental and hydrological interactions. Hence, the highway geotechnical engineering is crucial for the design of embankments, retaining walls, slopes, and other highway-related structures.

Speech:

Cyclic behaviour of unsaturated subgrade soil considering principal stress rotation

Chao Zhou, Professor, The Hong Kong Polytechnic University

A Data Augmentation and Intelligent Detection Method for Road Diseases Based on 3D Ground Penetrating Radar and Deep Learning

04 Jiong Zhang, Professor, Shandong University

The principle of void detection and equipment research and development of the lower foundation of the rail transit track structure

Bowen Hou, Professor, Beijing Jiaotong University

Recycling of construction waste in earthen cover system for slope stability

Haowen Guo, Professor, Harbin Institute of Technology, Shenzhen

Soil Water Migrating under Freezing-Thawing Cycles and Reinforcing-Wicking Integrated Treatment

Chuang Lin, Associate Professor, Harbin Institute of Technology

Cyclic behaviour of unsaturated subgrade soil considering principal stress rotation

Chao Zhou* and Baolin Dai Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University

Abstract:

When subjected to traffic loads, soil elements experience a stress path with both deviatoric stress variation and principal stress rotation (i.e., a continuous rotation of principal stress directions). It has been revealed that principal stress rotation (PSR) has a great impact on soil behaviour, leading to greater strain accumulation and reduced resilient modulus compared with conditions where PSR is absent. However, previous studies on PSR effects have been generally limited to saturated and isothermal conditions, despite subgrade soil experiencing daily and seasonal variations in temperature and suction. In this study, temperature- and suction-controlled units were implemented in the existing dynamic hollow cylinder apparatus. A series of cyclic shear tests with heart-shaped stress paths was conducted on compacted loess, taking into account the influence of PSR, suction (0, 10, and 30 kPa), and temperature (5, 20, and 40 ℃). Another series of cyclic tests without PSR was also conducted for comparison. Experimental results indicate that permanent strain increases and resilient modulus decreases with rising temperature and decreasing suction. Moreover, specimens subjected to PSR exhibit larger permanent vertical strain and smaller resilient modulus than those without PSR, as rotational loading induces additional deformation in anisotropic soils. More importantly, the additional strain induced by PSR increases with increasing temperature and decreasing suction. At zero suction, the permanent strain rises by 130% and 230% at 5 and 40°C when PSR is incorporated. As suction increases to 10 kPa, these values are 50% and 80%, as illustrated in Fig. 1. The coupled effects of PSR, temperature, and suction are likely due to the decrease in overconsolidation ratio (OCR) with increasing temperature and decreasing suction, with PSR effects being more pronounced at lower OCRs. In light of these new observations, a new semi empirical equation was proposed to model these coupled effects on resilient modulus, a critical parameter in pavement design. Comparisons between calculated results and measured data from this study and the literature demonstrate that this new equation effectively accounts for the combined influences of PSR, temperature, and suction.

A Data Augmentation and Intelligent Detection Method for Road Diseases Based on 3D Ground Penetrating Radar and Deep Learning

Zhang Jiong School of Civil Engineering, Shandong University, Jinan, Shandong, China. Email: jiongzhang@sdu.edu.cn

Abstract:

Road disease detection is critical for transportation safety and infrastructure maintenance, yet conventional manual inspection methods suffer from inefficiency and subjectivity. While 2D ground-penetrating radar (GPR) has limitations in spatial feature extraction, 3D GPR faces challenges including data scarcity, acquisition difficulties, and inadequate analytical methods for volumetric data. Current research predominantly focuses on 2D GPR image analysis, with limited exploration of 3D voxel processing and insufficient training data for deep learning models constrained by convolutional networks' local receptive fields. This study addresses three key scientific challenges: Data Acquisition: A dual-method approach constructs a high-quality 3D GPR dataset combining finite-difference time-domain (FDTD) simulations (modeling five typical diseases: voids, looseness, water-rich zones, delamination, and cavities with precise electromagnetic parameters) and field surveys using vehicular 3D GPR systems on urban roads and highways. Data Augmentation: A novel 3D Enhanced Generative Adversarial Network (3D EGAN) with Efficient Local Self-Attention (ELSA) is proposed to overcome data scarcity. The encoder-generator-discriminator architecture reduces computational complexity for high-dimensional voxel processing while ensuring physical consistency. Optimal augmentation strategies are investigated, including synthetic-to-real data ratios and fusion protocols. Disease Recognition: A hybrid 3D-Vam classifier integrates multi-scale 3D dilated CNNs (local feature extraction), Transformers (global spatial dependencies), and Mamba (efficient sequential modeling). This synergistic framework captures complex spatial patterns and long-range dependencies in volumetric data. Experimental results demonstrate: FDTD simulations successfully generate physically accurate 3D disease databases; 3D-EGAN enhances data diversity while preserving electromagnetic properties (validated by t-SNE visualization and Fréchet Distance metrics); The 3D-Vam model achieves state-of-the-art accuracy (92.7% F1-score) in five class disease identification, outperforming baseline models by 6.3–14.8%. This work provides a comprehensive solution spanning data synthesis, augmentation, and interpretable classification, offering practical tools for infrastructure diagnostics.

The principle of void detection and equipment research and development of the lower foundation of the rail transit track structure

Bowen Hou
Department of Road and Railway Engineering, Beijing Jiaotong University, Beijing, 100044 China, houbw@bjtu.edu.cn

Graphical abstract

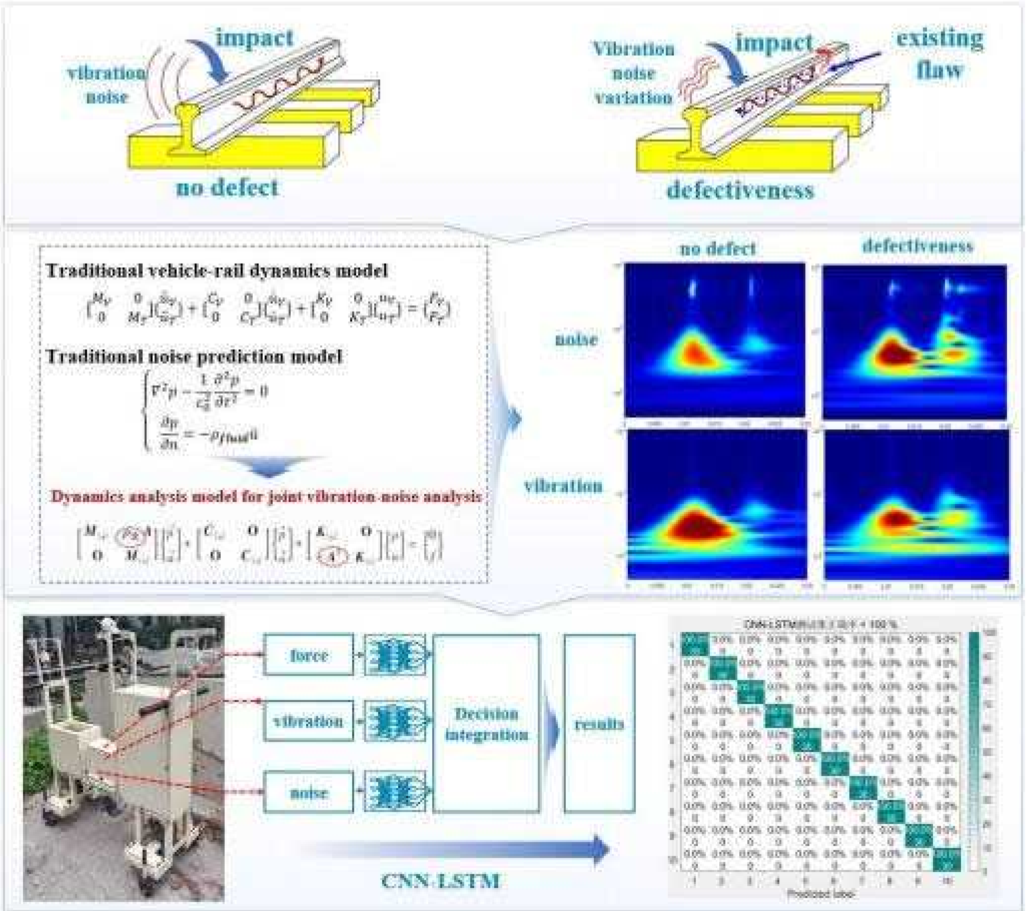

Figure 1 Graphical abstract

1 Objectives and Methodology

As China continues to advance the strategy of building a "Transportation Powerhouse," railways— the backbone of the national transportation network—have shifted from a phase of "large-scale construction" to "high-quality operation and maintenance." Currently, track condition assessment primarily relies on manual visual inspection and comprehensive inspection trains, which suffer from critical limitations: low detection efficiency, difficulty in identifying hidden defects, and inadequate quantification of structural deterioration trends. To address these challenges, this study leverages a fundamental principle: structural defects in track systems alter their acoustic and vibration responses under external loads. By exploring this mechanism, the research aims to achieve efficient, accurate, and flexible identification of all types of track defects, thereby reducing labor costs and intensity (especially in uninhabited areas) and ensuring the operational safety of track structures. In the theoretical phase, a vehicle-track acoustic-vibration coupling analysis model was established by introducing solid-gas boundary coordination conditions. This model enables the integrated calculation of vibration and noise in both vehicle and track systems under complex operating conditions, overcoming the limitations of traditional uncoupled analysis. Based on this model, a set of mapping relationships was constructed, linking the characteristics of strong vibration, complex flow field-induced vibration, and noise to specific types of track damages. Furthermore, a novel acoustic vibration joint evaluation method was developed for assessing track structure and service status. Experimental validation using impulse excitation (applied via a hammer) demonstrated that this theoretical method achieves an overall defect identification accuracy of 90%-92.5%, confirming its reliability. Building on the above theory and integrating deep neural network algorithms, a dedicated detection device was developed. This equipment features automatic hammering with precisely fixed impact positions, ensuring consistent excitation and data acquisition. After three iterations of optimization, the device has been successfully applied in field tests on Beijing Subway Lines 6 and 16 (tunnel environments) and the Xuzhou-Lanzhou Passenger Dedicated Line (high-speed scenarios). It effectively identifies common defects such as fastener failure, rail corrugation, and through cracks, and exhibits exceptional performance in detecting hidden defects (e.g., track slab voids and ladder sleeper voids) with an accuracy of 95%. The device has been highly praised by application units for its efficiency and precision. This research provides a robust theoretical and technical framework for high performance track defect detection, contributing to the establishment of a smart maintenance system for railways and ensuring the safe, reliable, and cost-effective operation of rail transit networks.

2 Major results and findings

Table 1 Major research results

Category	Key Indicators	Results
Theoretical	Method for Detecting Void in the Substructure of Track Structure	accuracy rate: 90-92.5%
Apply	Detection Equipment for Substructure Diseases of Track Structure	accuracy rate: 95%

Recycling of construction waste in earthen cover system for slope stability

Haowen Guo [1], Qi Zhang [2], and Chuanxiang Qu [3]

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Graphical abstract

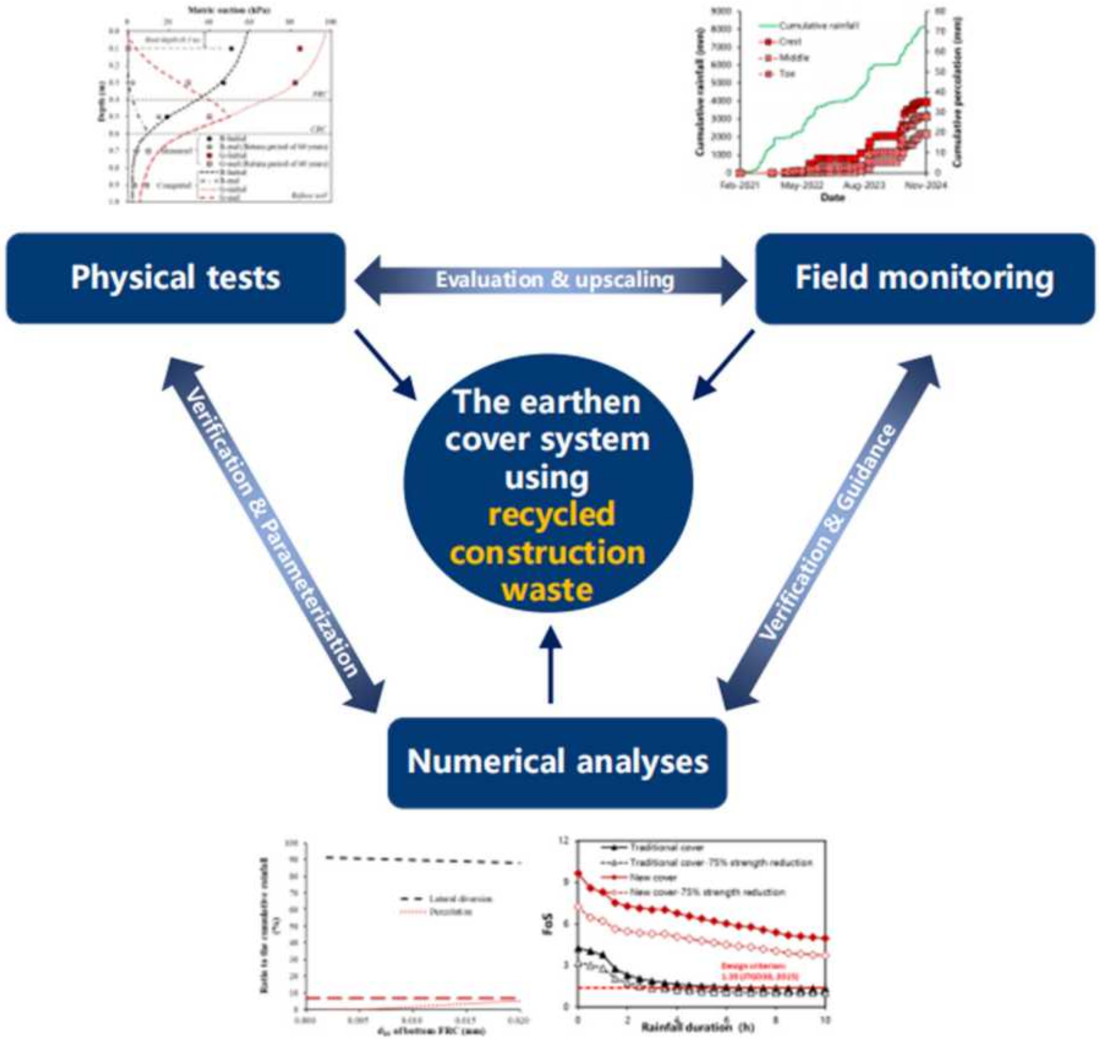

Figure 1 Graphical abstract

1 Objectives and Methodology

The continuous production and disposal of municipal solid waste (MSW) including construction waste have become a worldwide problem due to the increasing population and urbanization. Considering its simplicity, practicality and cost-effectiveness, landfilling remains one of the major methods to dispose of MSW. To reduce water percolation, most modern landfills are covered with geotextile composites and geomembranes. However, geomembranes are highly susceptible to interface instability and defects/holes which can influence their reliability. Consequently, a new all-weather three-layer cover system consisting of a low-permeability soil layer underlying the conventional two-layer capillary barrier has been proposed for humid climates and its performance verified. In this study, an integrated research approach is reported to investigate the hydrological effects of plants on the performance of a three-layer cover using recycled concrete. First, a series of laboratory column tests were carried out to quantify plant transpiration-induced soil matric suction in a vegetated three-layer cover system. Second, a three-dimensional full-scale test was performed to investigate the performance of the three-layer cover over the span of three years. Finally, the numerical back-analyses were conducted for verification against the model and field tests. A parametric study was performed to investigate the effects of particle size and layer thickness on the lateral diversion length and factor of safety (FoS) of the inclined three layer cover system under the 100-year return period rainfall of humid climates.

2 Major results and findings

Shrubs were found to be more effective than grass at preserving soil matric suction after heavy rainfall. Through the model test, it was revealed that the three-layer landfill cover system using recycled concrete could perform well even under extreme rainfall in the humid climate. Most of the rainwater (i.e., more than 90% of total precipitation) could be diverted from the soil surface and CCBE layers as surface runoff and lateral drainage. During the 3-year field trial in humid climates, the maximum measured annual percolation was less than 10 mm, which was less than 30 mm, as recommended by the USEPA. Due to the presence of new cover system, the FoS of the slope is 10 even at the end of a 100-year return period rainfall, while the FoS for the slope reinforced by traditional cover is 1.3 and slightly lower than the Chinese Design criterion.

Soil Water Migrating under Freezing-Thawing Cycles and Reinforcing-Wicking Integrated Treatment

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Transportation infrastructure in cold regions is highly susceptible to distresses such as frost heave and thaw weakening induced by cyclic freezing-thawing (F-T) actions and associated water migration, which severely compromises serviceability and longevity. This study systematically investigates the mechanisms of soil water migration during F-T cycles and proposes a novel, integrated reinforcing-wicking geotextile treatment technology designed to enhance the durability and resilience of road embankments in seasonal frost and permafrost areas.

Water is the pivotal factor governing the performance of infrastructure in cold regions. Under cyclic F-T conditions, water migrates towards the freezing front due to thermal gradients, forming ice lenses that cause frost heave. Subsequent thawing leads to water accumulation and a drastic reduction in soil strength, resulting in differential settlement, cracking, and other failures. Conventional mitigation methods often prove inefficient and costly.

A multi-faceted methodology was employed, encompassing laboratory experiments, numerical modeling, and field validation. Laboratory investigations utilized a one-dimensional F-T water migration device and a three-dimensional frost heave meter to quantify moisture translocation and heave mechanisms under controlled stress states. A self-developed temperature-controlled dynamic compression-shearing testing system was used to analyze the mechanical response of frozen-thawed soil under coupled thermo-hydro-mechanical (THM) loading and simulated traffic. The hydraulic performance of the wicking geotextile, including its soil-water characteristic curve (SWCC) and hydraulic conductivity function (K-function), was critically evaluated and compared to non-wicking alternatives. Field studies were conducted on two representative case histories: the G214 Highway on the Qinghai-Tibet Plateau (addressing permafrost degradation-induced settlement) and the Dalton Highway in Alaska (addressing frost boils).

The main findings conclusively demonstrate that the wicking geotextile effectively drains both capillary and gravitational water under minimal hydraulic gradient, thereby significantly reducing the water content in the subgrade and suppressing the formation of ice lenses. The integrated treatment provides combined reinforcement and lateral drainage functions. Field monitoring over a 12-year period on the Dalton Highway confirmed the long-term efficacy of the technology, with the test section remaining virtually free of frost-thaw-related damage. This resulted in substantial cost savings, estimated at $1.5 million in construction and $2.5 million in maintenance over a 12 mile section. While the treatment on the G214 highway, combined with insulation and piles, could not entirely halt permafrost degradation, it effectively mitigated its adverse effects on road performance. A coupled THM numerical model was successfully developed and validated to simulate the long-term (20-year) evolution of the humidity and stress fields in treated embankments.

This research provides significant theoretical insights and practical engineering solutions. It advances the understanding of the coupled THM processes governing soil behavior under F-T cycles. The proposed reinforcing-wicking geotextile presents an efficient, sustainable, and cost-effective ground improvement technique, offering a robust strategy for enhancing the resilience of transportation infrastructure in cold regions. Keywords: Freezing-thawing cycles; Water migration; Wicking geotextile; Subgrade treatment; Resilience enhancement.

Parallel Session J2

Topic: Multi-Scale Performance Enhancement Technologies for Transport Infrastructure

Chair: Xianhua Chen, Professor, Southeast University Cochair: Bo Li, Professor, Lanzhou Jiaotong University

Speech:

Asphalt layers for CRTS of Highspeed Railway

Xianhua Chen, Professor, Southeast University

The real-time pavement distress detection system based on edge-cloud collaborative computing

Yucheng Huang, Associate Professor, Soochow University

Vehicle Load Identification and Pavement Response Monitoring Using Roadside MEMS Accelerometers and Embedded Piezoelectric Sensors

Qian Zhao, Post Doctor, China Railway Design Corporation

Asphalt layers for CRTS of Highspeed Railway

Xianhua Chen, Southeast University

As an essential component of the waterproofing and drainage system in high-speed railway subgrades, the waterproof sealing layer functions as an external barrier to prevent surface water infiltration into the subgrade structure. It plays an indispensable role in ensuring subgrade stability, bearing capacity, and mitigating frost heave and thaw settlement-related distresses.

Monitoring data from passenger-dedicated lines in Northeast China (e.g., Harbin-Dalian and Harbin-Qiqihar High-Speed Railways) indicate that frost heave deformation primarily occurs in the subgrade surface layer, underscoring the critical need to control surface water penetration. However, current fiber-reinforced concrete waterproof sealing layers exhibit deficiencies such as poor frost resistance and susceptibility to cracking. Given China's expanding high-speed railway network and the demands of cold-region construction, developing more stable and durable waterproof sealing solutions is of paramount importance.

This paper systematically summarized long-term research experience Southeast University of asphalt-based waterproof layers in high-speed railways. An integral design method for asphalt layer in the coupling wheel-rail-track-subgrade system was presented, as shown in Figure 1.

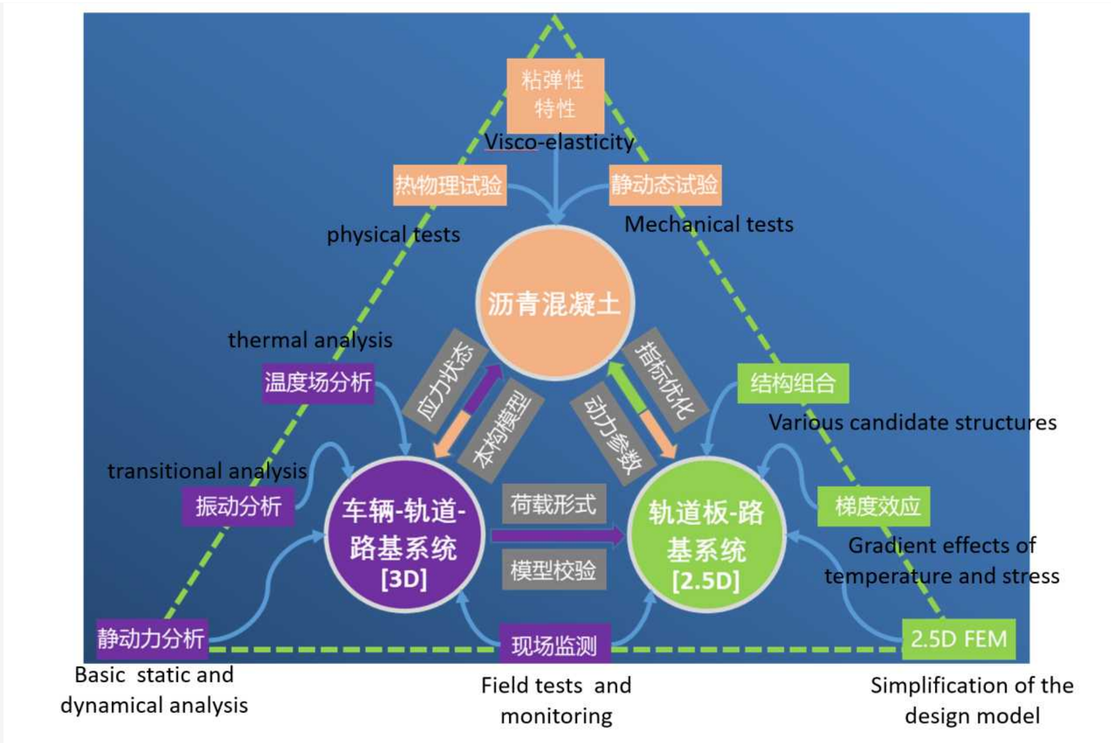

Fig. 1 A integral Design methods for asphalt layer in the coupling wheel-rail-track-subgrade system

Material Characterization

Asphalt concrete can be macroscopically characterized as a multiphase composite material, comprising:

- A hierarchical spatial network of aggregate structures (macro to meso-scale)
- Voids
- Asphalt mortar
- Mortar-aggregate interfaces (micro-scale)

The skeleton state of aggregates, asphalt mortar performance, and asphalt-aggregate interactions critically influence the high/low-temperature performance, fatigue resistance, and moisture damage resistance of asphalt concrete.

Theoretical Analysis, Design and Performance Evaluation

By analyzing the operational and construction conditions of high-speed railway subgrade waterproofing layers, we employed coupled train-track-subgrade dynamic theory and refined finite element modeling to assess how asphalt concrete support layers affect track structure and subgrade responses.

Innovative Solutions

Considering material properties, structural design, and construction requirements, we developed:

- Composite-modified asphalt with high-content crumb tire rubber powder
- Self-compacting asphalt concrete
- Rich-binder dense asphalt concrete
- Corresponding material specifications, construction techniques, and quality control standards

Implementation and Validation

A semi-analytical finite element-based design method and computational software for railway asphalt layers were established. These solutions have been standardized and successfully applied in over ten projects, including the Harbin-Qiqihar and Beijing-Zhangjiakou High-Speed Railways, with 15 years of performance monitoring.

Key Findings

1. Properly designed asphalt concrete layers provide:
    - Long-term 3D waterproof protection
    - Adjustable vibration damping for track structures
    - Tolerance to differential deformations
2. Scientifically constructed layers exhibit ultra-long service life (>60 years).

Conclusion

This integrated approach demonstrates that asphalt concrete waterproof sealing layers are a technically and economically viable solution for cold-region high-speed railways, combining durability, constructability, and performance adaptability.

The real-time pavement distress detection system based on edge-cloud collaborative computing

Zhiyuan Zhang, Yucheng Huang
School of Rail Transportation, Soochow University, Suzhou, 21511 China, ychuang@suda.edu.cn

Graphical abstract

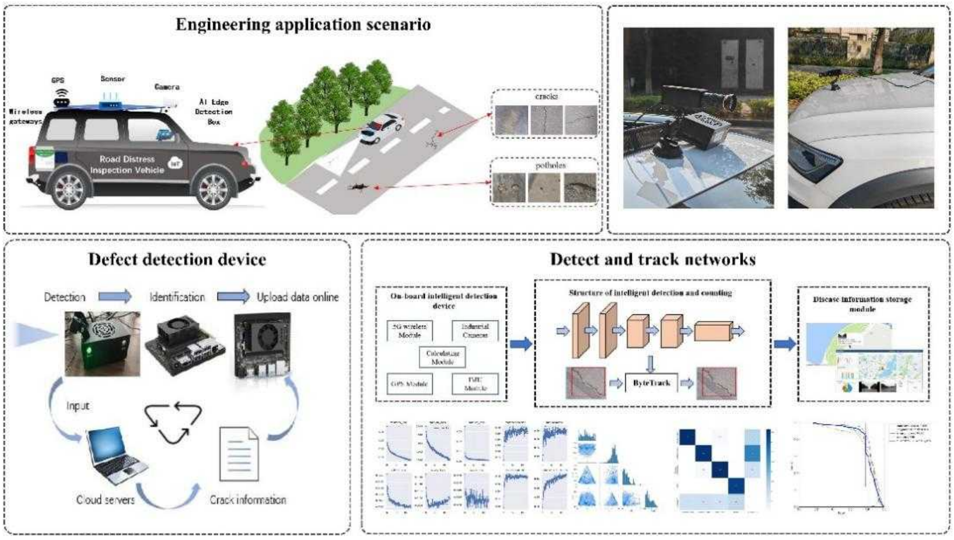

Figure 1 Graphical abstract

1 Objectives and Methodology

Research Background and Gap

Transportation infrastructure maintenance faces critical challenges with traditional manual pavement inspection methods suffering from low efficiency, safety risks, and subjective factors. While deep learning-based detection methods show promise, existing approaches require extensive computational resources that exceed edge device capabilities, creating a fundamental gap between detection accuracy and deployment feasibility for real-time field applications.

Research Objectives

This research develops a comprehensive real-time pavement distress detection system addressing computational efficiency while maintaining high accuracy. Primary objectives include: (1) designing a lightweight detection model for edge device deployment, (2) ensuring real-time detection of multiple pavement distress types, and (3) implementing cloud-edge collaborative architecture for comprehensive road monitoring.

Methodology

The methodology employs YOLO-LFE (YOLO with Lightweight Feature Enhancement) built upon YOLOv8n with three key innovations: (1) Integration of lightweight MobileNetV3 backbone to reduce parameters and computational complexity, (2) Enhanced Spatial Pyramid Pooling (ESPP) based on human visual perception for improved small object detection, and (3) Enhanced Asymptotic Feature Pyramid Network (EAFPN) addressing semantic gaps during feature fusion.

The system incorporates ByteTrack multi-object tracking to eliminate redundant detections, deployed on NVIDIA Jetson Orin Nano edge devices. Data collection involved 2,984 images from Suzhou City roads with four distress types: transverse cracks, longitudinal cracks, alligator cracks, and potholes.

2 Major results and findings

YOLO-LFE demonstrates significant efficiency gains: 32.5% fewer parameters and 37% lower computational demand than YOLOv8n, with 2.3% higher precision. Field tests confirm real-time detection at 85 km/h. The edge-cloud system integrates detection, tracking, and data transmission, enabling large-scale infrastructure monitoring. These results are validated in Table 1 and Table 2.

Table 1 Ablation Study Results

Baseline	MobileNetv3	ESPP	EAFPN	Precision	Recall	F1	Parameters	GFLOPs
YOLO v8n	-	-	-	0.892	**0.745**	0.811	3006428	8.1
	√	-	-	0.851	0.728	0.785	2351966	5.7
	-	√	-	0.897	0.759	0.822	3605100	8.7

Table 2: Performance Comparison of Detection Models

Model		Memory footprint/ MB	Precision	Recall	F1-score	MAP@0.5	Parameters	GFLOPs
One-stage	SSD	92.1	0.849	0.588	0.695	0.625	24.1M	137.2
	RetinaNet	139	0.940	0.490	0.644	0.523	36.4M	82.3
Transformer	RT-DETR-X	772	0.858	0.726	0.786	0.766	67.3M	232.4
	RT-DETR-ResNet101	708	0.848	0.758	0.800	0.774	61.8M	191.4
YOLO Variant	YOLOv6(n)	32.7	0.881	0.702	0.781	0.775	4.2M	11.9
	YOLOv7(tiny)	71.3	0.852	0.723	0.782	0.780	37.2M	105.2
	YOLOv9(c)	390	0.869	0.757	0.809	0.801	51M	238.9
	PD-YOLO(n)	39.3	0.864	0.762	0.809	0.793	20.4M	46.9
Two-Stage	Faster_rcnn	315	0.652	0.857	0.741	0.779	41.1M	193.8
	Grid_rcnn	491	0.456	0.838	0.591	0.753	64.2M	307.3
	YOLO-LFE(n)	**4.24**	**0.915**	**0.731**	**0.813**	**0.803**	**2.01M**	**5.1**

Design, Preparation, and Performance Study of High-Performance EPS

Concrete

Ji Yuan [1]
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Graphical abstract

Figure 1 Graphical abstract

1 Objectives and Methodology

This study introduces three methods to enhance the performance of EPS concrete. The first method involves adding microbeads to EPS concrete, reducing the water-to-binder ratio to make the EPS concrete more compact, thereby improving its mechanical and durability properties. The second method incorporates high-toughness polypropylene fibers into the EPS concrete, which not only enhances its toughness but also improves its durability. The third method involves wrapping the EPS particles with a cementing material before incorporating them into the EPS concrete. This wrapping process significantly improves the mechanical properties and durability of the EPS concrete.

2 Major results and findings

(1) A modified EPS particle reinforcement technology is proposed, and experiments confirm that the modified EPS particles can significantly improve the uniformity, mechanical properties, and durability of EPS concrete, revealing the enhancement mechanism of concrete based on EPS particle encapsulation modification.

(2) The addition of microbeads can improve the workability, mechanical properties, and durability of EPS concrete.

(3) The use of HTPP fibers can enhance the mechanical properties and durability of

EPS concrete.

(4) Based on the three methods for enhancing the performance of EPS concrete mentioned above, high-performance EPS concrete can be produced, expanding the application range of EPS concrete. It can be used as a structural material and has the potential to replace traditional PC components in certain areas for the production of prefabricated components.

Vehicle Load Identification and Pavement Response Monitoring Using Roadside MEMS Accelerometers and Embedded Piezoelectric Sensors

Qian ZHAO [1], Linbing WANG [2], and Zhoujing YE[3]
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1 Objectives and Methodology

This study develops an integrated framework for vehicle-pavement interaction analysis through three complementary investigations:

(1) Roadside MEMS Accelerometer Experiments

Field Testing: We deployed Micro Electro Mechanical Systems (MEMS) accelerometers on pavement surfaces and collected vibration data under controlled conditions using a Full-scale Accelerated Loading Tester.

Test Parameters: Vehicle speeds were systematically varied from 5 to 22 km/h, lateral distances between wheel center and sensors ranged from 0.4 to 0.9 m, and wheel loads were applied from 0 to 150 kN.

Data Acquisition: Vertical and lateral accelerations were sampled at 1 kHz and compared against Finite Element Method (FEM) predictions from literature.

(2) Embedded Piezoelectric Sensor Analysis

Modeling Framework: A 1/4 vehicle vibration model was coupled with a 3D finite element pavement structure embedded with piezoelectric sensors.

Validation: The model was calibrated using in-situ strain measurements from full-scale accelerated loading tests and literature-derived vibration profiles.

Controlled Variables: Experiments assessed impacts of axle loads (static/dynamic), vehicle speeds (10 – 60 km/h), and pavement roughness graded per IRC standards (Class A – C).

(3) Systematic Technology Review

We critically evaluated sensing technologies (MEMS, piezoelectric, strain gauges) considering policy constraints, climate impacts, and error propagation mechanisms.

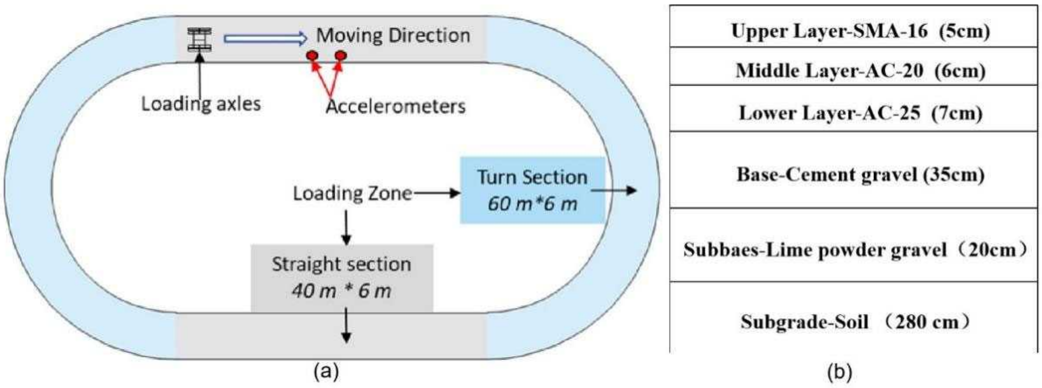

Figure 1.1 (a) Layout of the full-scale Accelerated Loading Test; (b) Pavement structure and materials

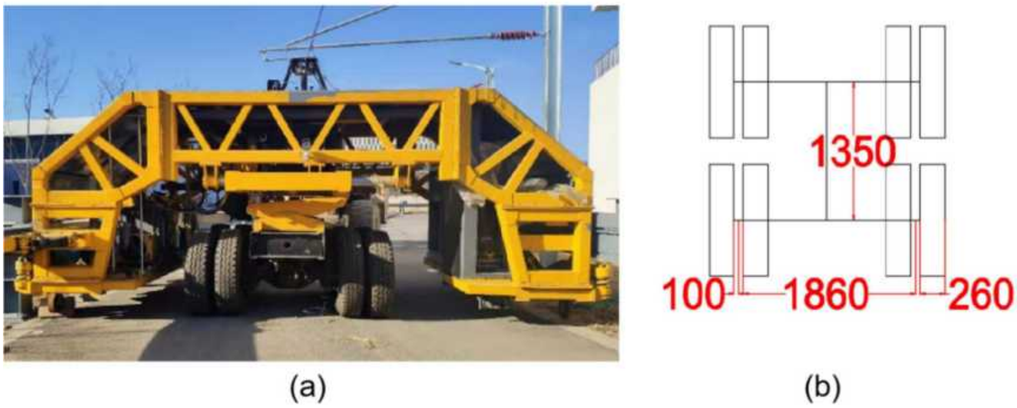

Figure 1.2 (a) Front view of the Loading axles; (b) Top view and the size of the frame (unit: mm)

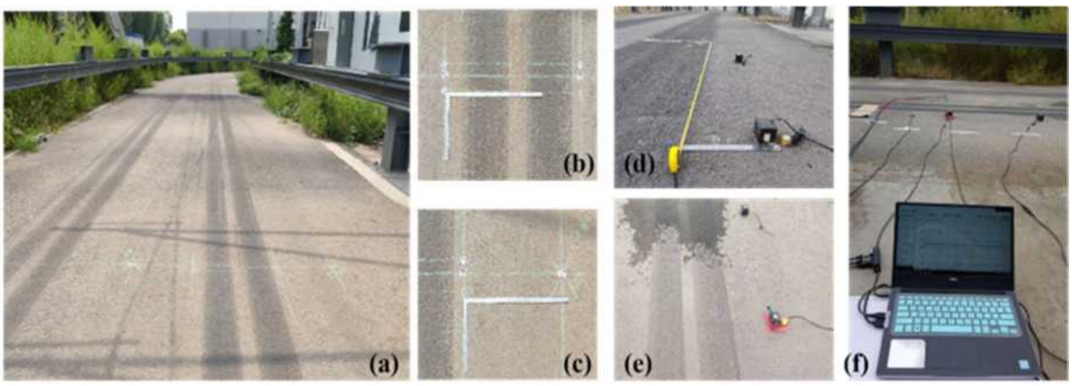

Figure 1.3 Deployment of the field tests

2 Major results and findings

2.1 Results

(1) MEMS Sensor Performance

A. Vertical peak acceleration increased linearly with vehicle speed within the tested range (5 – 22 km/h, R^2 > 0.95).

B. Vertical acceleration decreased following a power-law decay (expressed as *$y = 2.18x^{-0.85}$*) as lateral distance increased from 0.4 to 0.9 m.

C. Vibration energy demonstrated strong linear correlation with total vehicle load (correlation coefficient *r = 0.885*).

(2) Embedded Piezoelectric System Response

A. Both vertical acceleration and piezoelectric voltage output increased linearly with applied load.

B. Transverse strain peaks exhibited nonlinear surge under overload conditions (e.g., +42% increase at 40% overload).

C. When pavement roughness degraded from Class A to Class C, average vertical acceleration amplified from -10 mg to -39 mg, and maximum triaxial vibration growth occurred within 0 – 200 mm depth.

2.2 Conclusions

(1) Roadside MEMS sensors provide reliable monitoring of vehicle speed, lateral position, and load within operational limits; Optimal MEMS placement should be set at a certain lateral distance from the wheel path based on power-law attenuation characteristics.

(2) Roadside MEMS sensors provide reliable real-time monitoring of vehicle speed, lateral position, and load within operational limits (5 – 22 km/h). Embedded piezoelectric systems enable early detection of overload-induced damage through nonlinear transverse strain responses.

(3) This dual-sensing approach aligns with industry trends toward multi-sensor fusion, non-contact technologies, and AI-optimized data processing as identified in the technology review.

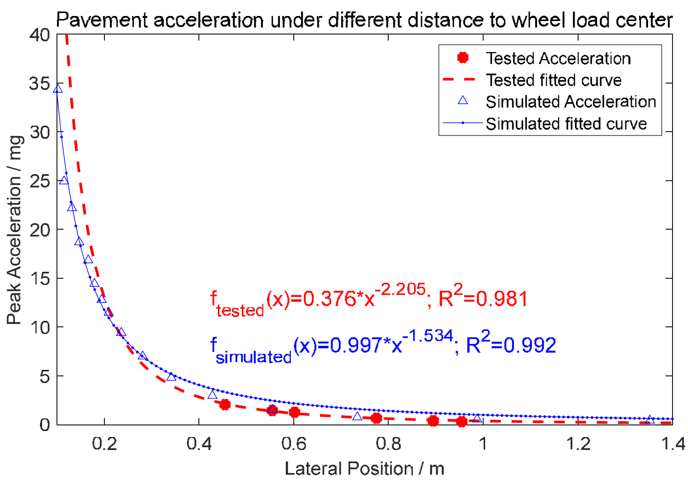

Figure 2.1 Vertical acceleration trends versus lateral position (0.455-0.955 m)

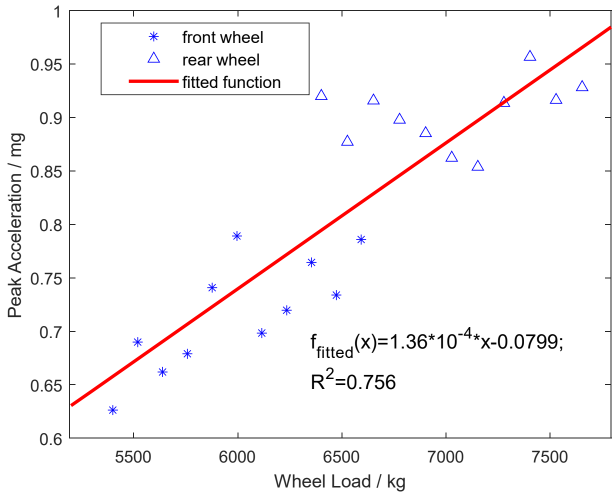

Figure 2.2 Vertical peak acceleration trends versus wheel load (5,400-7,700 kg)

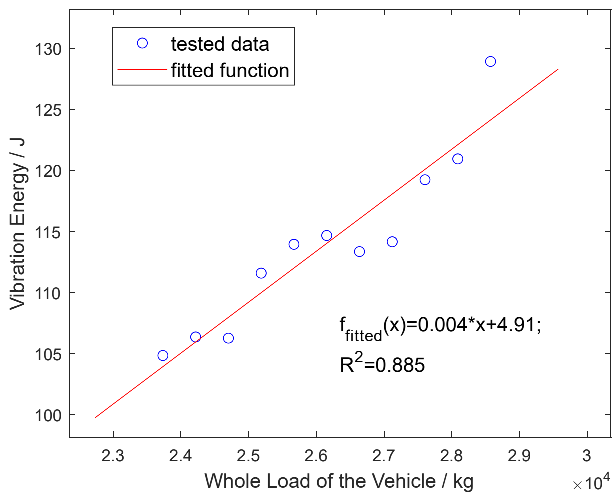

Figure 2.3 Vertical vibration energy trends versus whole load of the vehicle (23,730-28,570 kg)

Paralel Session A3

Topic: AI-Powered Smart Roads: Next-Gen Infrastucture and Colaborative Vehicle-Road Ecosystems

Chair: Xinyi Zhu, Professor, Tongji University

Introduction:

As a crucial component of the "human-vehicle-road" system, the intelligent technology of roads is particularly crucial for achieving high-quality transportation. However, existing studies rarely consider the feasibility of improving traffic safety and efficiency from the perspective of roads. With the rapid development of intelligent technologies such as AI, road facilities are expected to be endowed with more precise perception capabilities, more efficient decision-making abilities, and more diverse service capabilities, bringing new opportunities for achieving high-safety and high-efficiency urban transportation. In the actual application process, the development of intelligent roads also faces many challenges. Generally, these can be summarized as three aspects: "difficult perception", "difficult positioning", and "difficult guidance".

"Difficult perception" and "difficult positioning" mainly manifest in the limited perception capabilities of single vehicle intelligence, such as low resolution for distant targets, which is easily overlooked and has occlusion issues; it is difficult to obtain blind area information at turns and information about conditions beyond the line of sight. These problems largely affect the safety and reliability of autonomous driving; at the same time, intelligent vehicles developed based on intelligent networking and autonomous driving in complex urban environments are prone to losing data, such as missing road information under complex road surfaces, missing positioning information in urban canyons, and data packet loss in mobile vehicle groups, which can cause vehicles to fail to timely avoid obstacles during driving. "Difficult guidance" mainly manifests in the low visibility and poor dynamic regulation of traditional roadside guidance facilities (such as smart street lamps and other roadside guidance facilities) in complex traffic environments, thereby bringing significant safety hazards. A large number of practices have proved that relying solely on the intelligence of vehicles and traffic control is difficult to solve the frequent occurrence of traffic accidents and increasingly prominent congestion problems. The separate intelligent networking vehicles and autonomous driving technologies are prone to missing road information, positioning information, and communication information in complex urban environments such as complex road signs, urban canyons, and mobile vehicle groups. To make up for these deficiencies, intelligent roads, as an important component of full-scenario vehicle-road collaboration, can provide a large amount of data support, supplement massive data for full-scenario vehicle-road collaboration, and integrate vehicle-road information to achieve the goal of assisting decision-making and guidance. Therefore, it is urgent to develop intelligent road technology, by having road facilities undertake some perception tasks, adding or changing perception perspectives, and enabling them to work together with intelligent vehicles, so as to obtain more comprehensive perception information and break through the predicament of vehicle-road collaboration.

With the deep empowerment of artificial intelligence technology, intelligent roads have evolved into a "transportation life form" with three core functions of autonomous perception, precise positioning, and active guidance. Their perception system uses a heterogeneous sensing network composed of roadside millimeter-wave radars, laser radars, and multispectral cameras to achieve all-weather and all-element traffic environment cognition; the positioning system integrates feature matching technology to provide centimeter-level high-precision positioning services, effectively compensating for signal blind areas; the guidance function relies on edge computing nodes and distributed decision algorithms to achieve from microscopic lane-level speed suggestions to macroscopic regional traffic flow optimization. This integrated intelligent road, which combines "perception - positioning - guidance", is building a new generation of traffic infrastructure with metabolic evolution characteristics through physical carriers such as adaptive pavement materials, dynamic markings, and roadside facilities.

Speech:

AI-empowered Smart Sensing Road for Vehicle-Road Collaboration

Xingyi Zhu, Tongii University

Surface texture optimization of prefabricated pavement

Wei Sheng, Dawei Wang, Huailei Cheng, Yuan Li, Gengren Hao, Rui Zhang and Yuhong Wang, Harbin Institute of Technology,[2]The Hong Kong Polytechnic University

Validation and Demonstration of intelligent road Engineering with integrated perception and guidance

Chuanfu Sheng, Zhiguo Zhao, Yuhong Wang, The Hong Kong Polytechnic University

The Intelligent Traffic Guidance Based on Novel Pavement Markers for the Diversion Areas of Expressways

Xiangyu Feng, Bo Yu1, Dongfeng Li, Zehong Zhu, Tongji University

Validation and Demonstration of intelligent road Engineering with integrated perception and guidance

Haili Jiang, Shanghai Highway and Bridge (Group) Co., Ltd

Engineering-adaptive Pavement Maintenance Decision-making Model: a Reinforcement Learning Approach from Expert Feedback

Wenyuan Cai, Tongii University

AI-empowered Smart Sensing Road for Vehicle-Road Collaboration

Xingyi Zhu
Tongii University

Safety and efficiency are the core concerns of the transportation industry. According to the survey results of the National Bureau of Statistics, in 2021, there were 273,098 traffic accidents in China, with 62,218 deaths, over 90% of which were caused by motor vehicles. In addition, traffic efficiency has long been a problem. Take Shanghai as an example, the average speed on the city's central roads during peak hours in the morning and evening is only 16 kilometers per hour. Traffic congestion not only wastes passengers' time but also leads to economic losses, energy waste, and unnecessary carbon emissions. According to statistics, the annual economic loss due to traffic congestion accounts for 20% of the disposable income of urban residents. Therefore, improving the safety and efficiency of transportation is of great significance to the development of the transportation industry and society.

Based on the above background and demands, this project is committed to comprehensively enhancing the intelligent level of road infrastructure through AI technology, focusing on solving three core problems in complex urban environments: difficult environmental perception, difficult precise positioning, and difficult efficient guidance. The research will systematically explore the technical implementation path of intelligent roads under AI empowerment, and build a technical architecture and standard system that meets the characteristics and development needs of megacities. Specifically, in the aspect of perception, the research will explore the fusion algorithm of multi-source heterogeneous data to break through the bottleneck of environmental cognition in complex scenarios; in the aspect of positioning, it will develop new road-assisted positioning technologies to fill the positioning blind spots in areas where satellite signals are blocked; in the aspect of guidance, it will innovate dynamic collaborative control strategies to achieve intelligent regulation of traffic flow. Through technological innovations in these three dimensions, a "perceptible, controllable, and serviceable" intelligent road system solution will be ultimately formed, providing new technical support and practical paradigms for improving the quality and safety level of urban transportation. This research not only has important theoretical value but also provides a feasible technical path for the construction of smart cities and the implementation of the strategy of a transportation power.

Surface texture optimization of prefabricated pavement

Wei Sheng[1], Dawei Wang[1], Huailei Cheng[1], Yuan Li[1], Gengren Hao[1], Rui Zhang[1] and Yuhong Wang[2]

[1]Harbin Institute of Technology,[2]The Hong Kong Polytechnic University

Surface texture significantly impacts the safety and durability of concrete pavements, yet traditional methods limit texture configurations. 3D printing allows for precise design and production of textures tailored to practical needs, including specific features like type, width, depth and spacing. This study employed the finite element method (FEM) to assess the skid resistance and mechanical performance of these manufactured textures. A tire-texture FEM model was created to simulate tire-pavement interactions, validated through novel experimentation. An explorative evaluation was then conducted using 9 FEM models with different texture feature combinations revealed, which found that texture depth has a weak effect on skid resistance and stress distribution. Subsequently, an in-depth analysis was performed on 27 FEM models using the texture features excluding texture depth. The results indicated that skid resistance is primarily influenced by texture width and spacing, while texture type affects the maximum and minimum principal stresses. A moderate to significant correlation exists between stress concentration and skid resistance, suggesting that improved skid resistance may decrease mechanical durability. Ultimately, the study identified an optimal textural configuration for concrete pavements, balancing skid resistance and mechanical properties.

Validation and Demonstration of intelligent road Engineering with integrated perception and guidance

Chuanfu Sheng[1], Zhiguo Zhao[1,] Yuhong Wang[1]

[1]The Hong Kong Polytechnic University

This research proposes a joint vehicle-road positioning method called "Road Marking Assisted Vehicle Positioning Method in Complex Urban Road Environments", which utilizes a low-cost, non-electronic road code as a source of end-of-road positioning information to address the problems of GNSS and inertial guidance in tunnels, elevated canyons, and other urban canyons where GNSS and inertial guidance are prone to fail and have low accuracy. The road code has a side length of 48 cm, encodes centimeter-level latitude and longitude heights in 8×8 cells, and is designed with 6 parity checks to prevent errors and tampering; at the same time, the supporting script can generate a pattern with one key, which is highly efficient to deploy. The vehicle-mounted lightweight detection network fuses large kernel attention and deformable attention, and is trained on datasets collected under multiple operating conditions, which can be accurately and stably decoded with good generalization performance. Based on PnP position estimation and factor graph optimization algorithms, the fusion of roadside coded information and on-board inertial navigation data yields real-time vehicle positioning information at the decimeter level. The real vehicle test in a 2.2km tunnel shows that the relative positioning accuracy is improved by >20% and the reliability is >90%, which can assist the vehicle to realize reliable and high-precision positioning.

The Intelligent Traffic Guidance Based on Novel Pavement Markers for the Diversion Areas of Expressways

Xiangyu Feng1, Bo Yu1, Dongfeng Li1, Zehong Zhu[1]
[1]Tongji University

The diversion area, as a key node where the internal and external traffic flows of the expressway converge, is a bottleneck section that restricts the operational efficiency and safety of the expressway system.

In order to ensure the efficient and safe operation of traffic flow in the diversion area and adapt to its complex and changeable traffic operation status, it is necessary to rely on dynamic and variable road surface intelligent guidance facilities to propose scientific and real-time guiding strategies for the diversion area of the expressway. This study focuses on constructing an intelligent traffic guidance strategy based on novel pavement markers, achieving the prediction of the traffic status and real-time guiding decisions in the diversion area of urban expressways.

This study designs a type of novel pavement markers and, based on this, proposes an intelligent traffic guidance decision-making method for the diversion area of the expressway. The research results can effectively improve the operation safety and traffic efficiency of the diversion area, providing a new theoretical basis and technical path for the refined and intelligent real-time guidance of the traffic in the diversion area of urban expressways.

Validation and Demonstration of intelligent road Engineering with integrated perception and guidance

Haili Jiang
Shanghai Highway and Bridge (Group) Co., Ltd

本项目基于拓扑优化理论提出了装配式智能道路结构-功能协同设计方法，结合工程实际应用需求，首次提出了一种基于 T 形螺栓与钢绞线协同紧固的可拆卸式装配式路面结构，通过工厂预制的方式，将地埋智能道钉矩阵、振动/磁场/转角多功能感知器件、自感知智能筋材、定位编码组件等器件集成在装配式智能路面预制板上，在保障路面结构承载能力的同时为路面板附加多种智能功能。。将多种器件的驱动算法一体化集成，形成了智能道路的多维可视化监管平台 1 套，实现了对智能道路的可视化监管，以及对“感知-定位-引导”功能的自动化运行。

本项目实现了对智能道路相关技术的工程应用，共打造了“感知-定位-引导”一体化智能道路的 4 项试点工程（其中上海市试点工程 3 项，香港 1 项），分别位于：闵行区 S4 沪金高速莘朱路下匝道路段、上海市内环高架及北横通道、同济大学智能网联测试基地以及香港文锦渡路。成功在高速公路、内环高架以及多种道路场景内应用智能道路技术，形成了多功能硬件集成的智能道路快速铺装施工工艺，且经过第三方权威机构检测，本工艺的单板装配时间≤1 小时，工程工艺技术就绪度达到 7 级。

装配式多功能智能道路试点工程的成功建设，为推进智能道路技术在大型城市多种复杂城市道路场景下的工程应用起到了重要作用，总体而言，所有试点工程的业主单位对本项目相关技术的应用效果均表示满意，为智能道路技术在上海市和香港特别行政区的进一步推广建设提供了良好的开端。

Engineering-adaptive Pavement Maintenance Decision-making Model: a Reinforcement Learning Approach from Expert Feedback

Wenyuan Cai
Tongii University

Rising highway mileage and lifespan are heightening road maintenance demands. With most research focusing on corrective maintenance, daily maintenance optimization is understudied, despite its prominence in practical projects. Oriented to daily maintenance, data-driven models often fall short due to difficulties of model establishment and solution under complex road conditions and vague maintenance rules, while the experts' decision lacks interpretability and consistency amidst multifaceted factors. To fill in the gap, the paper proposes a fine maintenance decision model, combining data-driven methods and expert knowledge via reinforcement learning from expert feedback(RLEF). The research uses a pavement performance prediction model based on pavement deterioration laws as the environment and employ reinforcement learning to optimize strategies in decision model. Furthermore, the model incorporates multidimensional experts' feedbacks in the reward function to learn the ambiguous decision rules. Real-world data validation demonstrates that the RLEF model can adapt to engineering scenario and application better as well as achieve superior cost-effectiveness.

Paralel Session A4

Topic: Driver Behavior Characteristics Analysis and Innovative Applications

Chair: Xiaohua Zhao, Professor, Beijing University ofTechnology

Speech:

Application of Driving Simulation Cluster System in Traffic Safety

Qingfeng Lin, School of Transportation Science and Engineering, Beihang University

Driver Supervisory Attention Management for Automated Vehicle

Penghui Li, Ni Zhang, and Shufen Zhu, School of Traffic and Transportation, Beijing Jiaotong University,

Driver-Automation Trust and Cooperative Driving Strategies for Intelligent Vehicles

Qingkun Li, Institute of Software Chinese Academy of Sciences

PODAR: A Generalized Vehicle Collision Risk Modeling Framework for Multi-Scenario Applications

Chen Chen, College of Metropolitan Transportation, Beijing University of Technology

Application of Driving Simulation Cluster System in Traffic Safety

Qingfeng Lin[1]

[1] School of Transportation Science and Engineering, Beihang University, Beijing 100191, China, linqf@buaa.edu.cn

The Driving Simulation Cluster System (Multi-user driving simulation system) consists of a set of independent and coordinated simulators—including driving simulators, pedestrian simulators, and bicycle simulators (see Figure 1). The system enables real-time interaction among different road users within the same virtual scenario. The system supports teaching and research in fields such as traffic safety, human-machine interaction, and autonomous-driving simulation testing. Subsequently, we introduced three studies: A car-following behavior model for drivers in foggy conditions; Drivers' eye-movement behavior in tunnels under varying lead vehicle type and lighting conditions; A decision-making model for autonomous vehicles considering pedestrian' s time pressure based on game theory and reinforcement learning.

a) Pedestrian simulator b) Driving simulator c) Bicycle simulator

Figure.1 Driving Simulation Cluster System (Multi-user driving simulation system)

Research 1: A car-following behavior model for drivers in foggy conditions

Low visibility in foggy conditions can impair drivers' operational abilities and is highly prone to causing accidents. Therefore, conducting in-depth research on driving behavior under foggy conditions is of great importance.

The purpose of this study is to collect foggy car-following data using a multi-user driving simulator, establish car-following models adapted to different visibility and speed conditions, and evaluate the adaptability of each model. In this experimental study, visibility and speed factors were considered (visibility was divided into five levels: 50m, 75m, 100m, 150m, and 200m; speeds were 40, 60, and 80 km/h). Based on the multi-user driving simulation system, a highway foggy car-following test scenario was designed, and driving simulation experiments were conducted.

The research results indicated that compared to the Gipps, IDM, Newell, and FVD models, the Gipps car-following model exhibits lower mean values and standard deviations than the other three models. This study enriches the theoretical research on driving behavior in foggy conditions and provides theoretical support for the technological development of vehicle driving assistance systems and traffic safety management in foggy weather.

Research 2: Drivers' eye-movement behavior in tunnels under varying lead vehicle type and lighting conditions

The enclosed nature of tunnel environments, along with special lighting conditions and ventilation constraints, can significantly impact drivers' speed control and lane-keeping abilities, leading to an increased risk of rear-end collisions and a higher likelihood of multi-vehicle chain collisions. Therefore, analyzing driver behavioral characteristics in tunnel scenarios has become a core research topic in traffic safety studies.

This study focused on three key factors: illumination, lead vehicle type, and secondary tasks. Based on a multi-user driving simulation system, we designed tunnel car-following and rear-end collision avoidance test scenarios, and conducted driving simulation experiments. The research analyzed the impact of illumination, lead vehicle type, and secondary tasks on driving behavior in tunnel sections.

The research results indicated that: 1) The driving section significantly affected drivers' eye movement behavior. Compared to entering/exiting tunnels, the average fixation duration when drivers drove in a tunnel was lower, while the percentage of fixation time and the percentage of fixation count were higher. 2) Secondary tasks significantly influenced drivers' fixation behavior. Compared to no secondary task conditions, the average fixation duration, percentage of fixation time, and percentage of fixation count were lower when performing secondary tasks. 3) The lead vehicle type showed no significant impact on drivers' eye movement. This study enriches the theoretical research on driving behavior in tunnel environments and provides theoretical support for the technological development of vehicle driving assistance systems and traffic safety management.

Research 3: A decision-making model for autonomous vehicles considering pedestrian's time pressure based on game theory and reinforcement learning

Due to the obvious randomness, pedestrian crossing behavior is hard to predict, which challenges the decision-making of autonomous vehicles (AVs). Recent solutions have been able to adapt to structured road scenes with crossing signals or markings. However, there is still a gap in extending the pedestrian-vehicle interaction (PVI) performance in structured road scenes to unstructured road scenes.

Therefore, this paper proposed a vehicle decision-making model considering pedestrian intention based on game theory and reinforcement learning (RL). We designed and conducted a simulation experiment based on a virtual reality platform. Then, leveraging game theory, we established a pedestrian crossing decision-making model considering pedestrian heterogeneity evoked by time pressure (TP). A reward function was developed to enhance driving performance by combining safety, efficiency, and comfort. The RL agent of AVs learns to control the vehicle speed in a pattern that maximizes cumulative rewards through trials and errors by interacting with pedestrians in the simulation environment. The results show that AVs can effectively and safely interact with heterogeneous pedestrians on unstructured roads based on the proposed model. This study contributes to developing AVs that interact better with pedestrians and improve traffic safety, efficiency, and user acceptance of autonomous vehicles.

Driver Supervisory Attention Management for Automated Vehicle

Penghui Li[1], Ni Zhang[1], and Shufen Zhu[1]

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Graphical abstract

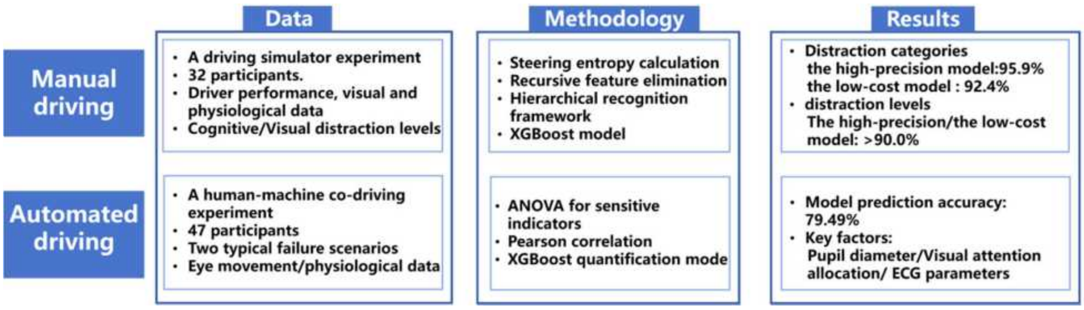

Figure 1 Graphical abstract

1 Objectives and Methodology

The current Level 2 and Level 3 automated vehicles operate in a human-machine co-driving mode, where drivers are still required to monitor the environment and take over in emergencies. Regulatory attention refers to the attention allocated by drivers to the driving task, and it directly affects risk perception and safe take-over in emergencies. Therefore, it is crucial to study real-time quantification technologies for driver's regulatory attention to optimize the design of take-over control systems in automated vehicles.

As for the traditional manual driving mode, a driving simulator experiment was conducted to collect data on driver performance, visual and physiological data under different levels of cognitive and visual distraction, which involved 32 participants. As for the automated driving mode, a human-machine co-driving experiment was conducted using a driving simulator, with two typical failure scenarios for automated vehicles: a preceding accident vehicle and a road collapse. Tasks such as N-Back and texting were used to induce driver attention shift. A total of 47 participants were recruited, and their eye movement and physiological data were collected synchronously. Statistical tests were used to analyze the impact of distraction types and levels on these three categories of indicators.

2 Major results and findings

Monitoring Driver Attention in Manual Driving Conditions. A vehicle steering entropy calculation method based on approximate entropy and sample entropy was proposed, considering the effects of sampling interval, gender, and individual differences. The results showed that approximate steering entropy and sample steering entropy were highly sensitive to cognitive distraction levels. Recursive feature elimination was used to select the optimal set of indicators for identifying distraction types and levels. The indicators based on driving performance were classified as low-cost recognition indicators, while those based on driving performance, eye movement, and physiological data were classified as high-precision recognition indicators. A hierarchical recognition framework for driving distraction was constructed, covering both category and level layers. The model hyperparameters were optimized using the sparrow search algorithm, and an improved XGBoost model was developed for hierarchical recognition of driving distraction. The results showed that the high-precision model and low-cost model achieved recognition accuracies of 95.9% and 92.4% for distraction categories, respectively. The high-precision model also achieved recognition accuracies higher than 90.0% for cognitive and visual distraction levels, while the low-cost model had lower recognition accuracy for distraction levels. Analysis of the driver workload characteristic curves indicated that both models performed well in distinguishing no distraction from visual distraction, but the low-cost model had some difficulties in distinguishing cognitive from visual distraction.

Monitoring Driver Regulatory Attention in Automated Driving Conditions. Before the system take-over voice was issued, 25 feature indicators, including eye movement, skin conductance, and electrocardiogram data, were extracted. Analysis of variance was used to explore the relationship between these indicators and the driver's regulatory attention level and take-over reaction time. The sensitive indicators for representing driver regulatory attention were selected accordingly. Pearson correlation analysis was used to screen key features, and an XGBoost model was developed to quantify driver regulatory attention based on eye movement and physiological indicators. The prediction accuracy reached 79.49%, and it was found that pupil diameter, visual attention allocation indicators, and electrocardiogram-related parameters were key factors for predicting driver regulatory attention.

This study provides theoretical and technical support for the development of high-sensitivity driver monitoring systems and safe take-over control in human-machine co-driving vehicles.

Driver-Automation Trust and Cooperative Driving Strategies for Intelligent Vehicles

Qingkun Li [1, 2]

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Graphical abstract

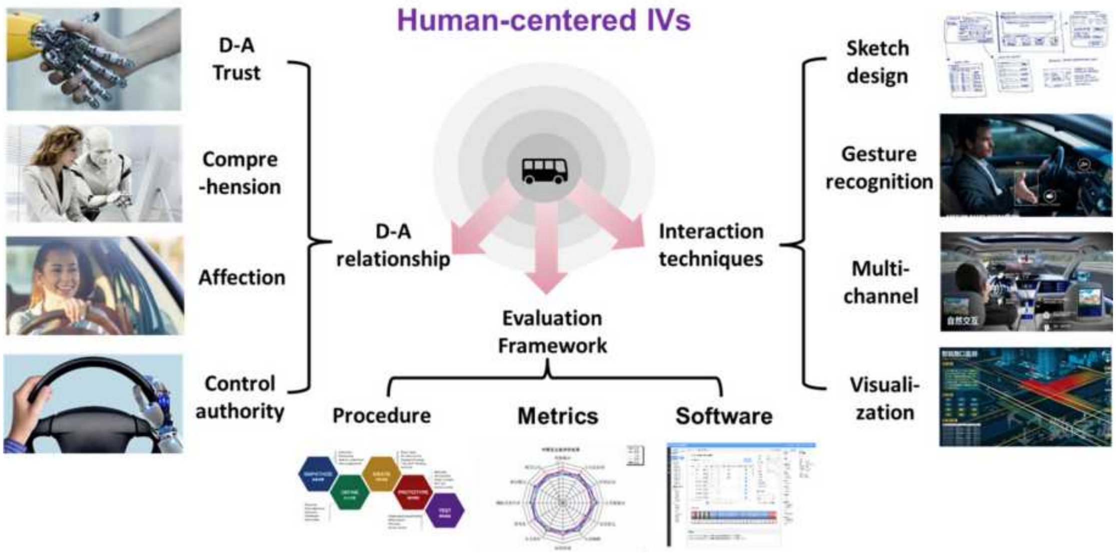

Figure 1 Graphical abstract

1 Background

Top-level design at the national level continues to be optimized, with policies driving the development of the intelligent vehicle industry in China. Human-computer interaction and collaborative have become the hot topic for conditionally automated vehicles, which are promising to become ubiquitous shortly. This work aims to summarize the existing key challenges and introduce our research achievements.

2 Major results and findings

Driver-automation relationship, in-cabin interaction techniques, and evaluation framework are the three main aspects of existing challenges for developing human-centered intelligent vehicles.

Driver-automation trust is important for the human-computer interaction and collaborative. To address the problems of low timeliness and poor accuracy of existing driver-automation trust assessment methods, we break through the bottleneck of real-time trust sensing technology with multimodal fusion and propose a deep-learning-based model.

Takeover readiness is a functional state regarding the driving capability during automated driving, which has been identified as a comprehensive construct with multiple related aspects. We proposed an adaptive cooperative driving strategy based on drivers' takeover readiness and surrounding traffic environment.

PODAR: A Generalized Vehicle Collision Risk Modeling Framework for Multi-Scenario Applications

Chen Chen[1]

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Graphical abstract

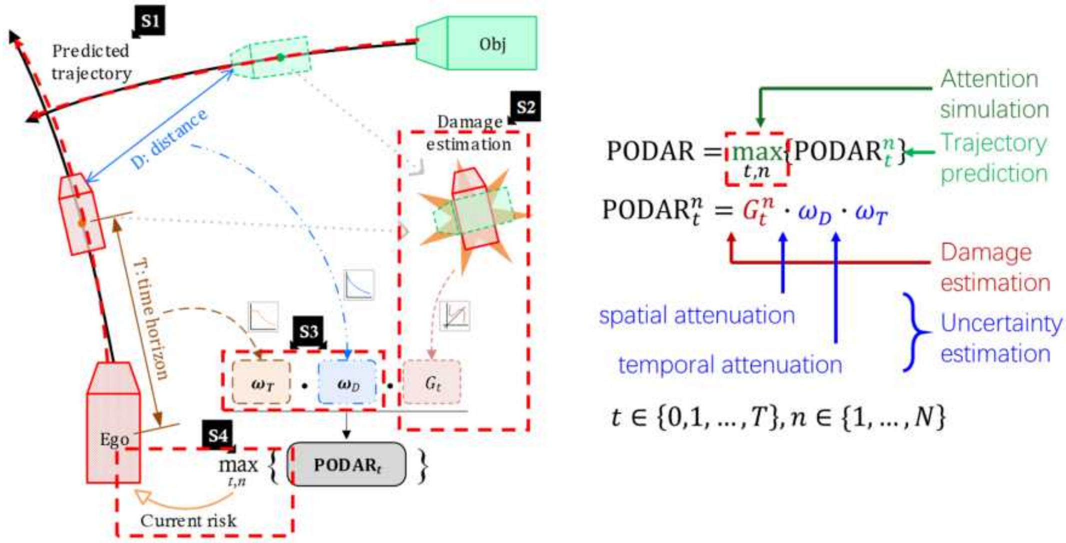


Figure 1 Graphical abstract

1 Objectives and Methodology

The primary aim of this research is to develop a generalized yet concise collision risk assessment framework, the **Potential Damage Risk (PODAR) model**, to deliver valid risk signals for diverse vehicular interactions without requiring manual scenario classification. Current risk metrics like Time-to-Collision (TTC), Safety Field (SF), and Driver's Risk Field (DRF) face limitations in handling non-conflict scenarios (e.g., parallel driving) or require complex scene-specific adaptations. PODAR addresses these gaps by **linking collision risk to potential damage** through a physics-inspired, modular approach.

Methodology:

The PODAR framework comprises four key steps:

1. **Trajectory Prediction**: Estimates future paths of the host and nearby vehicles using a constant acceleration model (extensible to advanced methods).
2. **Damage Estimation**: Computes potential collision damage (logarithmic function of kinetic energy, virtual mass, and speed differentials).
3. **Spatiotemporal Attenuation**: Applies exponential decay functions to project risk from future collision points to the present moment, accounting for spatial and temporal uncertainties.
4. **Attention Simulation**: Selects the highest risk value among all objects/prediction steps to mimic human focus on critical threats.

The model is calibrated using a driving simulation dataset, optimizing parameters (e.g., attenuation coefficients) via gradient descent to align with human risk perception (achieving R^2=0.942).

2 Major results and findings

Key Outcomes:

1. **Adaptive Trigger Distances**:
   - **Longitudinal Interactions**: For emergency braking, PODAR's trigger distances scale with speed and match theoretical stopping distances. In contrast, TTC thresholds vary inconsistently with speed.
   - **Lateral Interactions**: PODAR adapts to speed differentials, ensuring lateral gaps remain below safe margins, minimizing false alarms.
2. **Performance Validation**:
   - **Car-Following vs. Side-Pass Scenarios**: PODAR differentiates risks (e.g., rear-end collisions yield higher values than side-passing) and stays below warning thresholds in safe high-speed overtakes.
   - **Dynamic Cases**: In stop-and-go scenarios, PODAR provides early non-collision detection (1 s ahead) and collision warnings (2.5 s ahead), outperforming TTC, SF, and DRF.
   - **Lateral Conflicts**: Correctly identifies high-risk 90° collisions, while SF/DRF fail due to static assumptions.
3. **Generalization**:
   - Handles **multiple object types** (vehicles, pedestrians, infrastructure) by adjusting virtual mass (e.g., pedestrians M=1.2M = 1.2M=1.2 vs. cars M=1M = 1M=1).
   - Validated in **complex intersections** and real-world datasets (InD), showing accurate risk prioritization.

Comparative Advantages:

- **vs. TTC**: PODAR incorporates damage severity and works without path conflicts.
- **vs. SF/DRF**: Avoids misjudgments in lateral conflicts by simulating motion for both host and objects.
- **vs. PRM**: Reduces computational load and provides scalar risk values for real-time warnings.

Scalability:

PODAR's modular design allows integration of advanced trajectory predictors or user-defined risk preferences (e.g., aggressive/conservative driving styles via parameter tuning).

Paralel Session B3

Topic: Intermodal Transport and Smart Logistics

Chair: Cheng Cheng, Associate Professor, Southeast University
Cochair: Yong Zhang, Professor, Southeast University

Introduction:

Efficient and resilient intermodal transport-the seamless integrationof different transportation modes(road, rail, water, air)-isfundamentalto a sustainable global supply chain. Smart logistics, empowered bydigitalization, automation, and artificial intelligence,is the key enabler for optimizing this integration. This special session focuses on cutting-edge research, innovative technologies,and practical strategies to advance intermodal transport systems and smart logistics operations. We aim to foster discussions on leveraging intelligence to enhance efficiency, reliability, sustainability,and resilience across the entire logistics chain, from planning and execution to monitoring and optimization. Contributions addressing thechallenges and opportunitiesin creating interconnected, data-driven, and automated intermodallogistics networks are highly encouraged.

The following topics will be shown in this session, including but not limited to:

·Intermodal Network &Hub Optimization: Network design, hub location, transshipment efficiency,cost/time/emission trade-offs.

·Intelligent Operations: Real-time scheduling, collaborative management (CTM), resource utilization.

·Sustainable &Resilient Logistics: Low-carbon routing, alternativefuels emission management, network resilience.

·Smart "Last-Mile" Delivery: Urban distribution optimization for intermodal hubs, crowdsourced logistics, drone/robot delivery, smartparcel lockers, green last-mile solutions

Speech:

Development Trajectory of Smart Ports: Current Status and Future Prospects

HanKun Shia, Water Transport Research Institute, Ministry of Transport

Toward Greener Freight: Assessing the Policy Impact of "Modal Shift from Road to Railway"

Huiyu ZHOU, Shuqi Zhang, School of Economics and Management, Beijing Jiaotong University

A Bilevel Model for Robust Network Design and Biomass Pricing Under Farmers' Risk Attitudes and Supply Uncertainty

Qiaofeng Li, Halit Üster, Zhi-Hai Zhang, School of Systems Science, Beijing Jiaotong University

Development Trajectory of Smart Ports: Current Status and Future Prospects

HanKun Shia[1]

[1] Water Transport Research Institute, Ministry of Transport

Abstract

A smart port represents an innovative model and form of port development that integrates the deep application of next-generation information technologies to transform production, operational, managerial, and service processes. It enables digital processing and intelligent responses across all port elements, processes, and scenarios. The core of a smart port lies in leveraging technological advancements to reconfigure the multi-boundary, systematic port ecosystem, thereby achieving intelligent production and operations, efficient organizational coordination, open business innovation, and a convenient, reliable customer experience.

A smart port is characterized by five key attributes: comprehensive information perception, deep multi-system collaboration, real-time data interoperability, highly autonomous operations, and precise analytical and decision-making capabilities.

The evolution of smart ports can be categorized into five developmental stages: single-machine automation, system integration, data intelligence, ecological twin, and all-domain intelligence. The first stage, spanning from the 1990s to approximately 2010, was marked by single-machine automation and analog control, with human intervention still playing a dominant role. The second stage (2011–2015) was defined by system integration, point-to-point interconnection, and the initial dismantling of information silos. The third stage (2016–2020) focused on data-driven intelligence, vertical business closed-loop systems, and integrated software-hardware solutions. The fourth stage (2021–2023) emphasized ecological twins, collaborative equipment and systems, and green, low-carbon operations. The fifth stage, from 2024 to the present, is characterized by all-domain intelligence, large-model-driven capabilities, integration of virtual and physical systems, and self-learning functionalities.

The advancement of smart ports is closely tied to the continuous improvement and application of enabling technologies. Since the initial stage, automation and information technologies have played a foundational role throughout the development process. From the second stage onward, digital technologies began to assume a decisive influence. Starting from the third stage, intelligent technologies have driven rapid transformation and development.

The development of smart ports significantly enhances operational efficiency, promotes supply chain collaboration, improves service quality, strengthens safety risk management, supports green and sustainable practices, accelerates industrial integration and innovation, and reduces operational costs while improving economic performance. Through automated operations and intelligent scheduling, smart ports optimize resource utilization, reduce vessel waiting times, and expedite cargo turnover. By dismantling information silos, they foster closer cooperation among upstream and downstream stakeholders, thereby enhancing supply chain efficiency. Smart ports also deliver precise and convenient services, improving customer satisfaction. Advanced monitoring systems and early warning mechanisms ensure stable and secure port operations. Energy conservation, emissions reduction, and resource recycling

contribute to environmental protection. Emerging business models stimulate the growth of related industries. Labor and operational costs are reduced, enhancing economic competitiveness and injecting new vitality into the logistics industry, regional economies, and sustainable societal development. Ultimately, smart ports are driving the transformation of traditional ports toward a future of high efficiency, intelligence, and environmental sustainability.

Toward Greener Freight: Assessing the Policy Impact of "Modal Shift from Road to Railway"

Huiyu ZHOU[1], Shuqi Zhang[1]

[1]School of Economics and Management, Beijing Jiaotong University, Beijing, China

1.Introduction

The rapid expansion of transportation infrastructure has driven significant economic growth in China, but its unconstrained development has generated severe negative externalities, including threats to public health, safety, and rising environmental management costs. Road freight transport, dominated by heavy-duty diesel vehicles, remains a major contributor to air pollution and accounts for the largest share of energy consumption and CO_2 emissions within China's transportation sector. In response to these challenges, China's State Council launched the "Blue Sky Defense" action plan in 2017-2018, which emphasized optimizing freight transport structure by significantly increasing rail's share. This study provides a comprehensive evaluation of the "modal shift from road to railway" policy implemented since 2018, employing advanced causal inference methods to assess its multidimensional impacts across China's diverse regional contexts.

The policy mandates large enterprises handling over 1.5 million tons of annual freight to build railway spurs, particularly targeting coal mines and other bulk cargo operations. Local administrative offices monitor railway freight traffic shares and impose restrictions on road transport for non-compliant enterprises, while simultaneously discouraging road freight through increased environmental taxes and highway tolls. By 2020, key regions like Shanxi Province achieved remarkable success, with railway enterprises accounting for 80-90% of freight transport for priority commodities like fossil energy products. This research addresses three critical questions: (1) What are the policy's impacts on transport costs, congestion, safety, and environmental pollution? (2) How do these effects vary across regions? (3) What nonlinear relationships exist between socioeconomic factors and policy outcomes?

2.Literature review

The "modal shift from road to railway" policy in China is an initiative =implemented through administrative orders and government proposals aimed at guiding regions to use rail transport for large-scale material shipments as much as possible, thereby adjusting the structure of freight transportation. This policy reflects the country's macroeconomic control intent to optimize the transportation structure, considering both environmental benefits and transport efficiency.

As modes of transport, road and rail are substitutes for each other in the transport market, mainly in the sense that the withdrawal of one increases the market share of the other (Gañan et al., 2022). At the same time, railway transportation has the outstanding advantages of large volume of traffic, environmental protection and emission reduction (Rungskunroch et al., 2021; in et al., 2017), and thus it has been recognized by different countries and scholars in the process of freight structure transformation (Mizutani et al., 2020; Directorate-General, 2019).

This is further evidence of rail transport's economic and environmental friendliness and support the need for and importance of the "modal shift from road to railway" policy implementation. The literature on the effects of structural shifts in transport, especially from road to railway, can be divided into four main categories, as shown in Table 1.

Table 1 Summary of the possible dimensions of the policy effects.

Category	Perspective	Source
Direct costs	Economic externalities Large and centralised transport volume Low transport price, reliable transport volume, easy to form economies of scale Promote rational allocation of resources as well as economic development along the route	Lindsey and Santos (2020) (Vassallo and Fagan 2007) Zhang et al. (2022) Yan et al. (2022)
Traffic congestion	Roads wrongly undertake large-volume, long-distance freight transport, leading to congestion Congestion can be transferred to costing Reducing congestion in railway freight can increase economic benefits	Yang (2010) Struyf et al. (2022) Haywood et al. (2018) Wei et al. (2024) Li (2023)
Transportatio n	Transport safety Artificial intelligence for railway safety An increase in road freight transport	Liu et al. (2024) Tandrayen-Ragoobur, (2024)

safety	can lead to	Yang et al., (2015)
	a decrease in traffic flow rate, an increase in	Li (2023)
	lane changing rate, and the accident rate	
	Determine the average damage cost based on	
	property and personnel losses in accidents	
Environmental pollution	Heavy diesel vehicles pollute heavily	Du et al. (2017) Wang et al. (2024a)
	Pollution caused by freight transport carries	Rungskunroch et al. (2021)
	treatment costs	Zhu et al. (2023b) Liu (2018)
	Rail freight is more compatible with global	Rungskunroch et al. (2021)
	sustainable development	Zhu et al. (2023) Liu (2018) Yang et al. (2021)

3.Methodology

This study employs an innovative methodological framework combining causal forest analysis with partial dependence plots (PDP) to overcome limitations of traditional policy evaluation techniques. The causal forest approach, developed by Athey and Imbens (2016), extends random forests to causal inference, enabling identification of heterogeneous treatment effects (HTE) across different subgroups while addressing selection bias from non-random policy implementation. The model estimates Conditional Average Treatment Effects (CATE) through recursive partitioning of the feature space, creating locally homogeneous subgroups where policy impacts can be reliably assessed.

The analysis utilizes provincial and municipal panel data from 2011 to 2021, constructing four key outcome variables: (1) changes in freight turnover (ΔTV) calculated through vector autoregression (VAR) modeling of counterfactual scenarios, (2) congestion time reduction, (3) traffic accident reduction, and (4) CO_2 emission decreases. Control variables include railway mileage, employment density, transport prices, industrial structure, GDP per capita, fiscal expenditure, and fixed asset investment. The PDP component complements the causal forest by visualizing nonlinear marginal effects of key socioeconomic factors on policy outcomes, addressing the "black box" limitation of machine learning approaches.

4.Core Findings

The policy demonstrates statistically significant positive impacts across all evaluated dimensions. Benchmark regression results show policy coefficients of -0.127 for direct cost reduction, -0.304 for congestion alleviation, 0.191 for safety improvement, and -0.270 for environmental pollution mitigation. The causal forest analysis reveals substantial regional heterogeneity, particularly along China's Hu Line demographic divide. Southeastern provinces exhibit stronger policy responsiveness (HTE= 1.626) due to higher economic density and infrastructure development, while northwestern regions show more muted effects constrained by geographical and economic limitations.

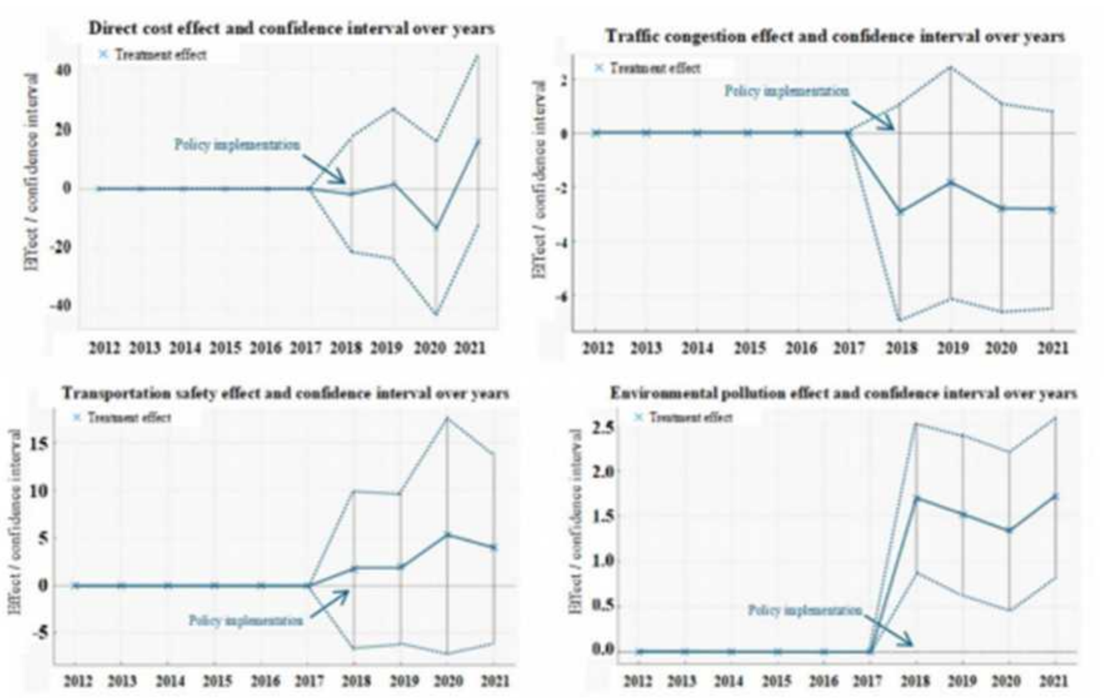


Figure 1. Policy impact after the implementation.

Nonlinear analysis uncovers critical threshold effects in policy implementation. Railway infrastructure demonstrates diminishing returns beyond 2,320 km of operating mileage (lnlen=7.75), where safety benefits peak before declining. Employment density in the transport sector shows a step-change effect at 0.55% (lnlabor=-5.2), beyond which additional workforce investments yield limited congestion relief. Similarly, railway freight pricing exhibits optimal effectiveness at 0.082 CNY/ton-km (lnfr=-2.5), with higher rates discouraging modal shift. The study also identifies a consistent one-year implementation lag, with safety improvements becoming most pronounced after this period.

5.Policy Implications and Conclusion

These findings carry important implications for sustainable freight policy design. In developed southeastern regions, policymakers should focus on operational optimization through professional workforce development and rail network efficiency improvements. For northwestern areas, balanced approaches are needed that consider ecological constraints while selectively expanding rail infrastructure in resource corridors. The identified threshold effects suggest avoiding blanket infrastructure investments beyond optimal scales and maintaining competitive rail pricing near 0.082 CNY/ton-km to maximize modal shift incentives.

The research contributes both methodologically and substantively to transportation policy literature. The causal forest+PDP framework provides a replicable approach for evaluating complex policy interventions in developing countries, while the empirical results offer concrete guidance for China's ongoing freight structure optimization. Future research should investigate city-level variations and policy interaction effects to further refine implementation strategies. As China continues its transition toward sustainable logistics, this study demonstrates that regionally tailored, evidence-based policies can effectively balance economic and environmental objectives in freight transportation.

A Bilevel Model for Robust Network Design and Biomass Pricing Under Farmers' Risk Attitudes and Supply Uncertainty

Qiaofeng Li[1], Halit Üster[2*], Zhi-Hai Zhang[3]
[1] School of Systems Science, Beijing Jiaotong University
[2] Department of Engineering Management, Information, and Systems (EMIS), Lyle School of Engineering, Southern Methodist University (SMU)
[3] Department of Industrial Engineering, Tsinghua University

In this paper, we present a bilevel design and pricing model that helps to design reliable and cost-effective biomass supply chain networks. The bilevel optimization model is used to account for the dynamic decision process between the biofuel producer and farmers, where the biofuel producer is the Stackelberg leader and farmers are Stackelberg followers. The biofuel producer makes the biomass price and network design decisions first; then, farmers react accordingly by making the biomass farming-related decisions. To address the computational complexity, we transform our bilevel optimization model to a tractable single formulation by using optimality constraints instead of KKT conditions, which are commonly used in the literature. In addition, for the first time in this study, we integrate harvesting time and frequency decisions within the biomass supply chain network design problem. We also consider the uncertainty in switchgrass yield and derive a robust reformulation to capture the farmers' risk-averse behavior in crop selection decisions for planting.

To solve the model with large-size instances, we devise a Benders decomposition algorithm. Moreover, we accelerate algorithm convergence by introducing surrogate constraints, strengthened Benders cuts, and in-out cut loop stabilization. Based on the computational experiments, we observe that the proposed solution approach performs significantly superior to the B&C and Benders decomposition approaches provided in CPLEX in terms of run times and gaps under the 1% optimality gap criterion.

We conduct a real-life case study in Texas to validate the capabilities of our mathematical model and solution approach. Several managerial insights are drawn from the case study results. (1) The biofuel producer has to offer a higher price premium to encourage farmers to harvest earlier. (2) Farmers' risk attitudes are an important factor that the biofuel producer should take into account when making pricing decisions. The biofuel producer should offer higher annual average prices when the farmers become more risk averse. Otherwise, risk-averse farmers will not plant switchgrass, and the switchgrass demand is not satisfied. (3) The adoption of multiple-harvest strategies can lead to significant cost savings and hedge against the effect of biomass deterioration, and (4) the biofuel producer chooses farms to cooperate by weighing the different farms' transportation benefits and price benefits. As unit transportation cost increases, the distant farms become less economical, and the biofuel producer will encourage farms that are close to the biorefineries to plant switchgrass by offering higher prices. Furthermore, as evidenced by the solution characteristics and the extensive analyses, our model remarkably captures the interactions and trade-offs among biomass harvesting decisions, biomass supply pricing decisions, and underlying logistics network design decisions to match the demand effectively and efficiently.

This research can be extended in several directions. First, further uncertainties in parameters (e.g., cost parameters and biomass demand) can be taken into account in the design of the biomass supply chain. Second, multimodal transportation networks (rail, barge, and truck) for delivering biomass can be introduced. Third, except for the economic objective of minimizing the total cost, the environmental objective function minimizing total emissions and some other social objectives can be considered.

Paralel Session B4

Topic: Advances in Smart Urban Mobility Technologies

Chair: De Zhao, Associate Professor, Southeast University
Cochair: Yu Zhou, Professor, Beihang University

Speech:

Development Trajectory of Smart Ports: Current Status and Future Prospects
HanKun Shia, Water Transport Research Institute, Ministry of Transport

Collaborative Perception for Intelligent Connected Vehicles in Complex Traffic Scenarios
Mingfang Zhang, Ying Liu, Jia Ma, Ye He & Li Wang, Beijing Key Lab of Urban Intelligent Traffic Control Technology

Microscopic Traffic Simulation and Vehicle Motion Optimization Technology in New Mixed Traffic Environments
Miaomiao Liu, School of Transportation Science and Engineering, Beihang University

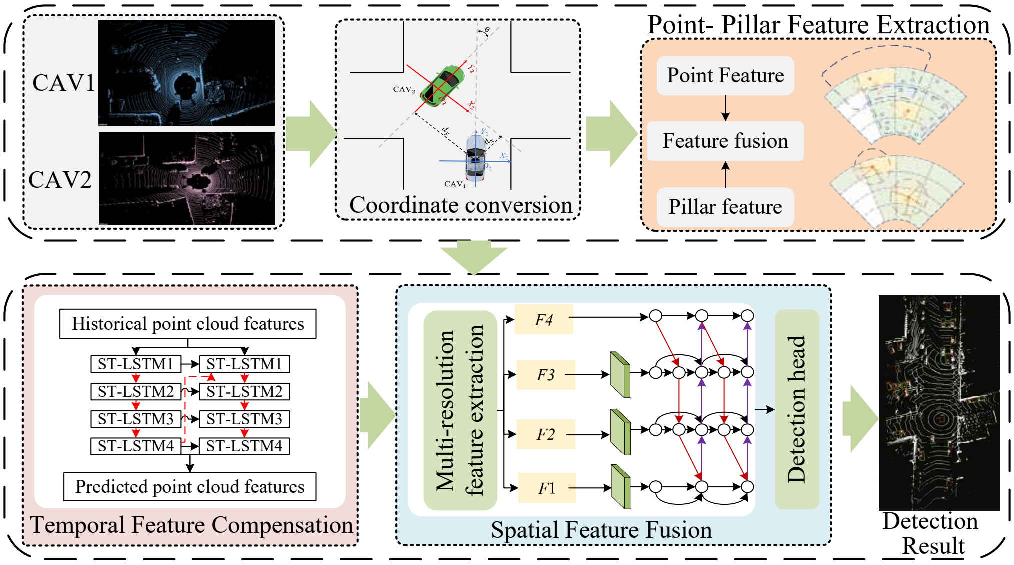
Multi-objective optimization design of transit network and operating frequency — considering passengers' choice behaviors under station congestion
MingZhang Liang, School of Transportation, Southeast University,

Research on Home Autonomous Driving Travel Itinerary Planning and Application Exploration
Qin Huanmei, Han Xiaojing, Lu Zhaolin, Wen Xiaohuan, College of Metropolitan Transportation, Beijing University ofTechnology

Collaborative Perception for Intelligent Connected Vehicles in Complex Traffic Scenarios

Mingfang Zhang, Ying Liu, Jia Ma, Ye He & Li Wang
Beijing Key Lab of Urban Intelligent Traffic Control Technology, North China University of Technology, Beijing, 100144 China,mingfang@ncut.edu.cn

Graphical abstract



1 Objectives and Methodology

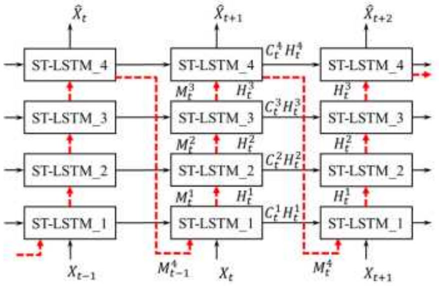
Accurate perception of the surrounding environment is essential for intelligent connected vehicles (ICVs) to achieve safe and reliable autonomous driving. 3D perception for individual vehicles is inherently constrained by occlusions, limited sensing range, and narrow perspectives. And cooperative perception is often vulnerable to communication latency and it always lacks sufficient fine-grained feature representation. Thus, we propose a point cloud collaborative perception framework based on a spatio-temporal feature compensation network. It consists of three modules as follows.

(1) Point- Pillar Feature Extraction

The raw point cloud is transformed into a unified coordinate system. Fine-grained local features are extracted using a cylindrical coverage-based sampling method to capture detailed spatial structures. In parallel, pseudo-image features are generated through a PointPillar network to encode global spatial patterns efficiently. The point-level and pillar-level features are subsequently fused to form a unified feature map, allowing the model to retain rich geometric details while maintaining computational efficiency.

(2) Temporal Feature Latency Compensation

To address the misalignment of features caused by communication latency, this module employs a spatiotemporal prediction network based on PredRNN. It takes the historical point cloud features received from surrounding vehicles and models their temporal dependencies using spatiotemporal LSTM cells. The predicted future point cloud features are synchronized with the ego vehicle's current perception, ensuring that multi-vehicle information is temporally aligned for cooperative detection.



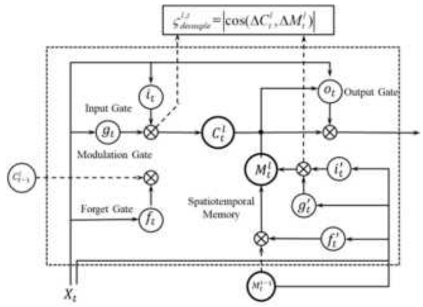


Figure 1 PredRNN Structure Figure 2 ST-LSTM Network Structure

(3) Spatial Feature Fusion Compensation

This module first aligns the spatial features transmitted from other vehicles based on their relative poses, and performs maxout-based aggregation in overlapping regions to construct a unified feature map. Bidirectional multi-scale feature pyramid network is introduced to fuse features from various resolutions, combining shallow and deep features through bottom-up and top-down pathways. This hierarchical fusion improves the robustness and accuracy of object detection across varied distances, scales, and occlusion conditions.

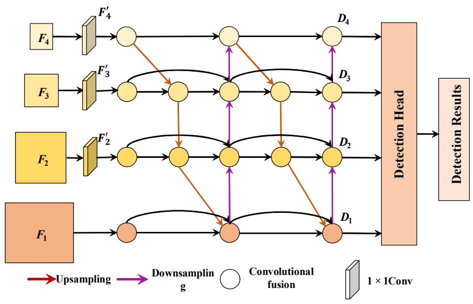


Figure 3 Bidirectional multi-scale feature pyramid network

2 Major results and findings

In order to demonstrate the performance of the proposed method, extensive experiments are conducted on both V2V4Real and self-collected urban driving dataset. As shown in Table 1, our approach achieves higher detection accuracy, especially under scenarios with communication delays. Notably, the PredRNN-based temporal compensation module enables the system to maintain stable performance even when significant network latency exists, and the spatial multi-scale fusion design enhances object detection robustness across varying distances and occlusion conditions.

Table 1 Comparison of algorithm performance under different latency conditions

Algorithm	V2V4real(AP@IoU=0.5/0.7)			Self-collected dataset (AP@IoU=0.5/0.7)		
	100ms	200ms	300ms	100ms	200ms	300ms
F-Cooper	0.697/0.413	0.524/0.346	0.305/0.173	0.587/0.406	0.484/0.323	0.302/0.143
CoBEVT	0.725/0.443	0.538/0.352	0.446/0.223	0.622/0.423	0.509/0.368	0.422/0.195
V2VNet	0.765/0.480	0.563/0.387	0.484/0.235	0.675/0.462	0.533/0.337	0.475/0.232
V2XViT	0.776/0.503	0.601/0.437	0.491/0.368	0.671/0.484	0.584/0.389	0.483/0.306
Ours	**0.798/0.5**	**0.713/0.52**	**0.549/0.43**	**0.726/0.5**	**0.636/0.4**	**0.532/0.3**

	41	**4**	**1**	**28**	**32**	**72**

Microscopic Traffic Simulation and Vehicle Motion Optimization Technology in New Mixed Traffic Environments

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Graphical abstract

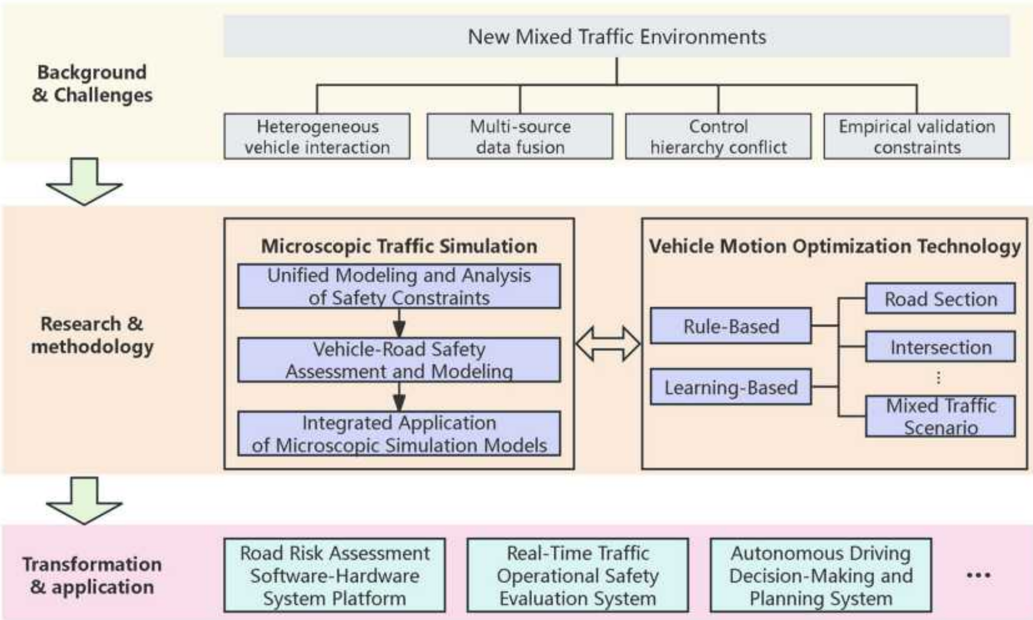

Figure 1 Graphical abstract

1 Objectives and Methodology

This study addresses the core challenges in new mixed traffic environments (e.g., coexistence of autonomous vehicles (AVs), connected vehicles (CVs), human-driven vehicles (HVs), and vulnerable road users), including safety-efficiency trade-offs, data quality issues, control-level conflicts, and experimental validation limitations. The goal is to develop high-fidelity microscopic traffic simulation systems and intelligent vehicle motion optimization technologies to achieve dynamic balance in safety, efficiency, and adaptability, promoting intelligent transportation development. Key methods involve a risk field theory-based unified quantification model within the RF-SIM microscopic traffic simulation system to assess 3D safety risks from moving objects, static environments, and traffic control; integrated with car-following, lane-changing, and intersection models, RF-SIM enables multi-source data fusion and 3D scene generation, creating a "physical world - digital modeling - algorithm validation" closed loop. Complementary vehicle motion optimization technologies include safety margin (SM)-based car-following control, cooperative passing for unsignalized intersections, and 3D strategies for signalized intersections (like priority-based sequencing, speed conflict resolution, and trajectory selection), augmented by improved Transformer architectures for trajectory prediction and RA-Attn-MTL DQN deep reinforcement learning to handle uncertainties from heterogeneous participants. Outcomes have been implemented in road risk assessment systems, real-time vehicle trajectory optimization, and driving simulator platforms, with demonstrations in Hunan and Shandong provinces, enhancing traffic efficiency by 20-40% and reducing delays and emissions.

2 Major results and findings

Introduce the major research results and findings with table and charts.

Table 1 Table name

Type	Name	Status
Paper	A unified driving behavior model based on psychological safety space	Published
Paper	Cooperative motion optimization based on risk degree under automatic driving environment	Published
Paper	A Cooperative Lane-Changing Method for Autonomous Vehicles Based on Dynamic Trajectory Planning	Published
Patent	A method to improve intersection traffic efficiency based on risk in autonomous driving environment	Accepted
Patent	A cooperative traffic management strategy for autonomous vehicles at intersections based on occupancy degree	Accepted
Patent	A vehicle trajectory prediction algorithm based on improved Transformer model	Accepted
Software Copyright	Real-time traffic safety evaluation system V1.0	Accepted

Multi-objective optimization design of transit network and operating frequency — considering passengers' choice behaviors under station congestion

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Graphical abstract

The transit network design and frequency-setting problem (TNDFSP) plays a critical role in urban transit system planning. Due to the conflict between the level of service and operating costs, extensive research has been conducted to obtain a set of trade-off solutions between the interests of users and operators. However, most studies ignored the effects of station congestion in TNDFSP, resulting in unrealistic solutions or a failure to achieve optimal design schemes. Therefore, this study investigates the multi-objective optimization of TNDFSP considering users' choice behaviors under station congestion. To address the problem, a multi-objective bilevel optimization model is first formulated. The upper level is a bi-objective optimization model with two conflicting objectives: minimizing users' cost and minimizing operator's cost. The lower-level problem is a passenger assignment problem under station congestion (PAP-SC). Moreover, a novel multi-objective evolutionary algorithm based on objective space decomposition (MOEA-OSD) is proposed to solve the complex problem. When dealing with multi-objective optimizations, a decomposition mechanism is developed to convert the problem into multiple subproblems. These subproblems are optimized using an evolutionary approach with newly designed selection process and elite preservation strategy to achieve desirable convergence and diversity. The computational results obtained using Mandl's benchmark demonstrate the efficacy of MOEA-OSD and the advantage of the proposed model in achieving more comprehensive trade-off solutions.

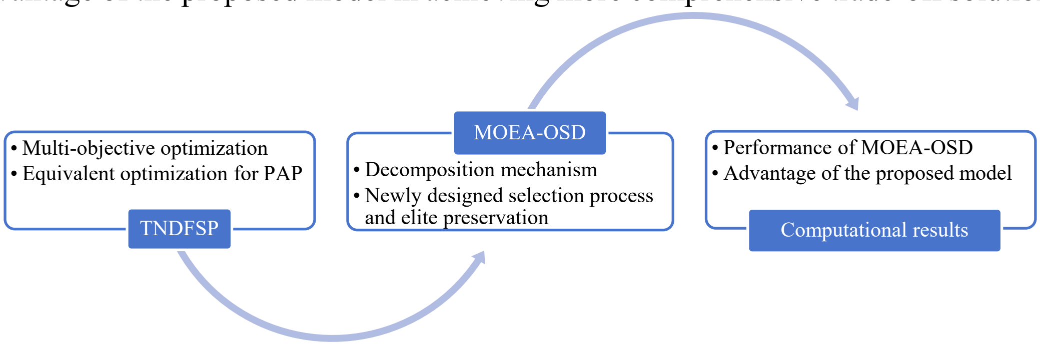

Figure 1. Graphical abstract

1 Objectives and Methodology

In this study, we investigate the multi-objective optimization of TNDFSP to obtain optimal trade-off solutions between user and operator costs. These solutions will provide the most effective design schemes that are optimal for users under different operating costs, or optimal for operators at different expenses of user cost. Thus, the operator can determine the final scheme according to resources and financial viability.

Different from previous studies, we assume that the station congestion is allowed when designing transit lines and their frequencies, so that optimal solutions can be found when operators cannot provide sufficient operating resources. Moreover, we consider users' choice behaviors that are more aligned with the reality, where waiting times are assumed to be a continuous function of station congestion levels and may impact users' choice behaviors. Users' perception of transfers and their choices interactions under congestion are also considered, thereby enabling the TNDFSP to obtain solutions that are rational and in accordance with users' interests.

To achieve these objectives, we propose a multi-objective bilevel optimization (MOBO) model to formulate the TNDFSP. The upper-lever is a bi-objective optimization with two conflicting objectives that are to minimize users' and operator's costs. At the lower-level, we propose an equivalent optimization problem to formulate the PAP with station congestion (PAP-SC), which is associated with a gap function that converges to zero at the UE state. To capture more realistic users' behaviors and unify the evaluation of user costs between the upper- and lower-level optimization, we formulate users' choices based on the line and node strategy and propose a modified travel cost function that reflects congestion and transfer impacts. Moreover, the constraints associated with the results of PAP-SC are relaxed and transformed into penalty functions, leading to a straightforward modeling framework for optimizing transit lines and frequencies simultaneously.

Due to the complexity of the problem, we propose a novel multi-objective evolutionary algorithm based on objective space decomposition (MOEA-OSD). When addressing multi-objective optimizations, the algorithm converts the problem into multiple subproblems, each of which focuses on optimizing only one objective while constraining the other objectives within certain intervals. These constraint intervals are dynamically scaled by equally decomposing the objective space based on the distribution of solutions, and associated subproblems are optimized using an evolutionary approach to approximate the Pareto optimal front. The decomposition strategy naturally enhances the capability of the algorithm to achieve evenly distributed solutions along each objective. Moreover, we propose a novel selection process to exert more pressure on evolution for breaking through the current Pareto front and an elite preservation strategy for balancing the convergence and diversity of the algorithm.

2 Major results and findings

To examine the efficacy of MOEA-OSD, we compare it with three metaheuristic approaches, including the well-known NSGA-II, NSGA-III, and MOSA. Five scenarios are considered, in each of which the number of transit lines to be established is 4, 6, 7, 8, and 12. The Pareto optimal solutions obtained from these approaches are illustrated in Fig. 2. As can be seen, solutions generated by the proposed MOEA-OSD dominate those of other approaches in most cases, i.e., a solution dominates another if some objectives can be improved without degrading the other objectives. In some scenarios, MOSA achieves operator-oriented solutions with lower fleet sizes due to its independent phase for optimizing a single objective. However, the phase-division mechanism also compromises the ability of MOSA to improve the overall Pareto front. Under the same number of iterations, the quality of the Pareto front obtained by MOSA is not competitive compared to other approaches. Additionally, it is obvious that the proposed MOEA-OSD can achieve evenly distributed solutions along each objective compared to other approaches.

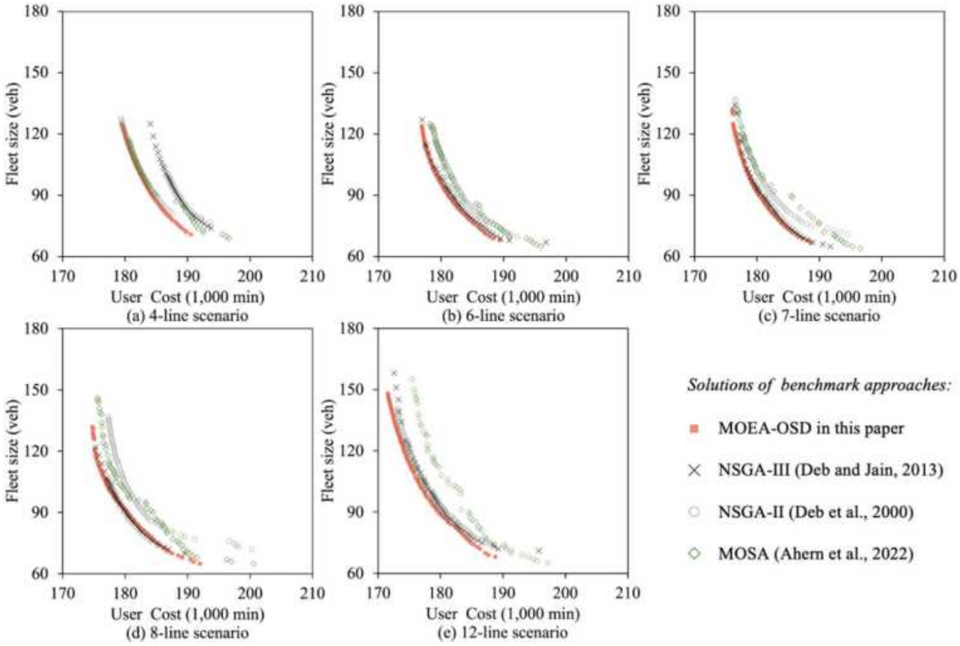

Figure 2. Results comparison in the five scenarios for (P1)-FS.

The integrated model for TNDFSP based on PAP-SC (denoted as (P2)-PAPSC), which is proposed in this study, is solved by the MOEA-OSD, and the results are compared with those obtained in traditional TNDFSP model based on frequency-share rule without considering station congestion (denoted as (P1)-FS). The results are illustrated in Fig. 3. It demonstrates that the Pareto front obtained from (P2)-PAPSC is more comprehensive than that of (P1)-FS in all scenarios. The user-oriented solutions achieve lower user costs, while the operator-oriented solutions further reduce the required fleet size. Tables 1 and 2 present the objective values of operator-oriented, operator-user balanced, and user-oriented solutions derived from (P1)-FS and (P2)-PAPSC, respectively. For example, in the 12-line scenario, the operator-oriented solution of PAP-SC further reduces the minimum fleet size to 57 vehicles. Compared to (P1)-FS, the network operation can optimize vehicle allocation and meet all demand with a 11-vehicle reduction, providing decision-makers with more feasible schemes when budged is limited. Similarly, the user cost can be saved 2,375 min if the operator has sufficient budget to allocate 178 vehicles. However, deploying a massive fleet size solely to minimize user costs may not be a reasonable option, because the marginal cost is too high for the operator. In other words, the reduction in user cost resulting from an increase in unit fleet size is too small.

The results and findings provide practitioners with more practical and managerial insights. First, operators can initially determine the acceptable range of fleet size according to their budget and subsequently select the solution with the highest marginal benefit for users as the final planning scheme. Second, accounting for station congestion is critical in TNDFSP. Completely avoiding congestion can lead to significantly higher operating costs, particularly in high-demand scenarios. A more practical approach for transit operators is to deploy common lines to handle heavy demand in key corridors while maintaining cost-efficiency. However, setting excessively high frequencies for these common lines is unnecessary; this would result in capacity wastage when the lines traverse low-demand areas. Instead, balancing frequency and capacity utilization ensures effective operations without resource overuse.

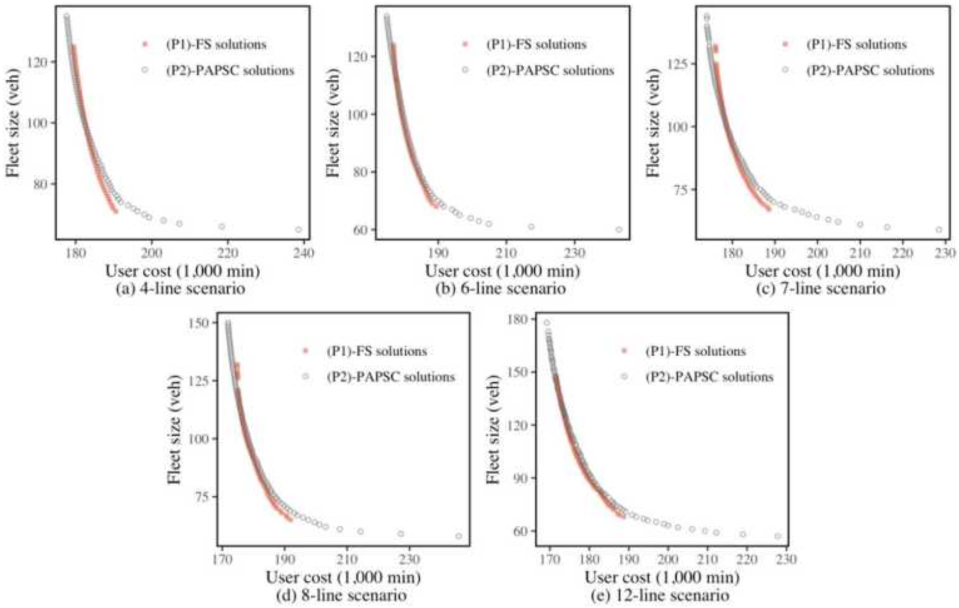

Figure 3. Results comparison of (P1)-FS and (P2)-PAPSC in the five scenarios.

Table 1. User-oriented, operator-oriented, and balanced solutions of (P1)-FS.

Scenario	(P1)-FS solutions Operator-oriented Fleet size (veh)	 User cost (1,000 min)	Operator-user balanced Fleet size (veh)	 User cost (1,000 min)	User-oriented Fleet size (veh)	 User cost (1,000 min)
12-line	68	188.753	107	176.011	148	171.581
8-line	65	191.931	98	178.159	132	174.733
7-line	67	188.611	99	178.807	132	176.051
6-line	68	189.428	96	179.918	124	176.922
4-line	71	190.529	98	182.783	125	179.418

Table 2. User-oriented, operator-oriented, and balanced solutions of (P2)-PAPSC.

Scenario	(P2)-PAPSC solutions Operator-oriented Fleet size (veh)	 User cost (1,000 min)	Operator-user balanced Fleet size (veh)	 User cost (1,000 min)	User-oriented Fleet size (veh)	 User cost (1,000 min)
12-line	57	227.772	117	175.087	178	169.206

8-line	58	245.803	104	177.406	150	171.864
7-line	59	228.477	101	178.498	144	174.011
6-line	60	242.932	97	180.154	134	174.934
4-line	65	238.615	100	182.338	135	177.608

Research on Home Autonomous Driving Travel Itinerary Planning and Application Exploration

Qin Huanmei[1] ,Han Xiaojing[1] ,Lu Zhaolin[1], Wen Xiaohuan[1]

[1] College of Metropolitan Transportation, Beijing University of Technology, Beijing,100124China,hmqin@bjut.edu.cn

Graphical abstract

Figure 1 Graphical abstract

1 Objectives and Methodology

（一）Research objectives: With the rapid development of autonomous driving technology, family travel patterns are undergoing significant changes. Existing studies pay more attention to the acceptance of AV by individual users, and lack of analysis of the travel coordination mechanism among members from the perspective of family units. The aim of this study was to:

1.Construct a family AV path optimization model based on the Traveling Salesman Problem with Time Window (TSPTW), and comprehensively weigh the time cost, travel cost and carbon emission cost.

2.Quantify the difference in travel efficiency between nuclear families (parents and children) and multi-generational families (including the elderly) under the traditional mode and AV mode.

3.Reveal the impact mechanism of AV technology on family travel satisfaction, vehicle sharing and sustainability, and provide theoretical support for smart transportation planning.

（二）Research Methodology：

1.Problem definition and model construction: Based on the Traveling Salesman Problem with Time Window (TSPTW), a home autonomous driving travel route optimization model is constructed. The model comprehensively considers the travel time cost of family members, the driving cost of autonomous driving cars, and the cost of carbon emissions, aiming to optimize the travel path for family members to share and use autonomous driving cars.

2.Objective function and constraint setting: An objective function is set to minimize the total cost of family travel. A variety of constraints are established, including active node access constraints, travel closure constraints, MTZ constraints

o avoid subloops, vehicle number synchronization constraints, and time window constraints to ensure the feasibility and practicality of the model.

3.Data collection and processing: Collect the travel activity information of family members through the daily travel log survey of family members, including the start and end of the activity, departure and arrival time, travel mode, activity duration, activity start time window, etc. At the same time, collect data on families' alternative travel plans in autonomous driving travel scenarios, as well as the weight ranking of families' attention to different travel costs.

4.Case analysis and model application: Select nuclear families and multi-generation families as cases, and apply the optimized model for analysis. Comparing family travel characteristics (such as the number of vehicles used, total mileage, empty mileage, total travel time of family members, etc.) and travel costs (including time costs, vehicle travel costs, carbon emission costs and total travel costs) under traditional travel modes and autonomous driving travel modes.

2 Major results and findings

Table 1 Comparison of different travel modes of typical nuclear families

Project	Indicator	Traditional travel Mode	Autonomous Driving Travel Mode	Change
Project	Number of vehicles used by households (units)	2	1	-1
	Total vehicle mileage (km)	62.4	99.4	+59.3%
	Vehicle empty mileage (km)	—	31.7	—
	Total travel time of family members on the road (min)	170	70	-58.9%
	Total detour time for	—	6	—

	family members (min)			
	Late departure time for family members from home (min)	—	37	—
	Early arrival time of family members (min)	—	37	—
	The sum of the time when the vehicle arrived at the event site early (min)	—	65	—
Project	Travel time cost of family members (RMB)	58.0	57.8	-0.3%
	Vehicle driving cost (RMB)	94.3	103.2	+9.4%
	Vehicle carbon emission cost (RMB)	4.2	3. 1	-26.2%
	Total travel cost (RMB)	61. 1	63.8	+4.4%

Table 2 Comparison of different travel modes of multi-generation families

Project	Indicator	Traditional travel Mode	Autonomous Driving Travel Mode	Change
	Number of vehicles used by	1	1	0

Project	households (units)			
	Total vehicle mileage (km)	37.8	72.6	+92. 1%
	Vehicle empty mileage (km)	—	31.9	—
	Total travel time of family members on the road (min)	346	60	-82.7
	Total detour time for family members (min)	154	13	-91.6%
	Late departure time for family members from home (min)	—	70	—
	Early arrival time of family members (min)	—	45	—
	The sum of the time when the vehicle arrived at the event site early (min)	—	52	—
Project	Travel time cost of family members (RMB)	106.8	88.6	-17.0%
	Vehicle driving cost (RMB)	55.6	74.5	+34%
	Vehicle carbon emission cost	2.5	2.2	-12%

	(RMB)			
	Total travel cost (RMB)	63.8	67.2	+5.3%

Based on CPLEX solver and MATLAB simulation, the following conclusions are drawn:

(1) Autonomous driving cars can significantly reduce the total driving time of family members (58.9% for nuclear families, 82.7% for multi-generational families), improve travel satisfaction and flexibility, and reduce carbon emission costs (nuclear families-26.2%, Multi-generational families-12.0%).

(2) However, the total mileage and empty mileage of vehicles increased significantly (up to 92. 1%), resulting in an increase of 4.4% to 5.3% in overall travel costs.

(3) In addition, although sharing autonomous driving cars can reduce the number of cars owned by families, it is necessary to weigh the contradiction between vehicle scheduling efficiency and waste of empty driving resources.

This study provides a theoretical basis for family travel collaborative planning, and proposes a practical direction for the scenario-based application of autonomous driving technology, such as the combination of dynamic scheduling algorithms and new energy technologies. Studies have shown that autonomous driving technology has both efficiency improvement and environmental friendliness potential in family travel, but its promotion requires further optimization of path planning and sharing strategies to alleviate mileage and cost pressures. The research results not only provide scientific support for the intelligent transformation of family travel modes, but also provide an important reference for the sustainable development of urban transportation and the realization of low-carbon goals.

Paralel Session C3

Topic: Digital Twin Modelling of Autonomous Road Infrastructures and Environment

Chair: Yuqing Zhang, Professor, Southeast University

Introduction:

Digital twin (DT) for road infrastructure integrates IoT, AI, and multiphysics modeling to create dynamic virtual replicas of physical assets, enabling real-time monitoring and predictive management. Recent advancements aim to overcome challenges such as data silos, computational limitations, and scalability through innovations like self-powered sensors, hybrid modeling techniques, and edge-AI frameworks. These developments are critical for addressing key issues including pavement deterioration, traffic safety, and climate resilience. Real-world implementations demonstrate DTs' potential to reduce costs and carbon emissions. The latest research is vital to accelerating the shift toward autonomous and sustainable infrastructure systems. Key topics in the relevant areas include but is not limited to:

(1) Digital Twin Framework for Road Infrastructure and Environment
(2) Self-sensing Technologies & Data Fusion for Real-time Monitoring
(3) Multiphysics/Multiscale Modelling of Road Materials and Structures
(4) Dynamic Data-Driven Hybrid Modelling for DT Real-time Updating
(5) High Performance and Edge Computing for AI-aided Predictions
(6) DT Implementations and Demonstrations in Road Environments

Speech:

Electrical Characteristics and Damage-Monitoring Performance of Self-Sensing Asphalt Concrete

Yangming Gao, Yuanyuan Li, Yi Da, Built Environment and Sustainable Technologies (BEST) Research Institute, Liverpool John Moores University

How to Update the Digital Twin? —A Fault Tree Risk Analysis for Pavement Infrastructure

Qiao Dong, and Ruiqi Li, Department of Roadway Engineering, Southeast University

Intelligent Inspection and Digital Management of Airport Pavement

Xu Yang, Chang'an University, Xian, China

Exploring the Application of Digital Twins in Infrastructure Engineering – Improving Asphalt Pavement Construction

Chonghui Wang, Aston University, UK.

Electrical Characteristics and Damage-Monitoring Performance of Self-Sensing Asphalt Concrete

Yangming Gao[1*], Yuanyuan Li[1,2], Yi Da[1]

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* Corresponding author: y.gao@ljmu.ac.uk

Graphical abstract

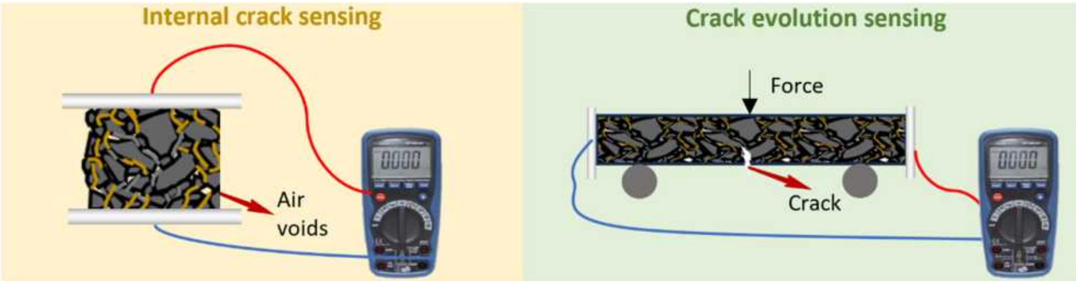

Fig. 1. Graphical abstract of this study.

1 Objectives and Methodology

Digital roads (DRs) have been proposed to inform design, construction, maintenance and operational decisions in-time, making roads safer, more resilience and more sustainable. However, current structural health monitoring (SHM) technologies for DRs, e.g., sensors, Cameras and Imaging Systems, Ground Penetrating Radar (GPR) require significant amounts of manpower and time and the use of costly equipment and are not able to detect internal micro-damage and its development in-time. This study aims to characterise the electrical properties and damage-monitoring performance of the self-sensing asphalt materials to facilitate the realisation of real-time monitor pavement internal early-age damage.

Six groups of Marshall specimens with conductive additives such as graphite powder (GP) or carbon nanotube (CNTs) and steel fibres (SF) were prepared. Their electrical resistivity was examined using a digital multimetre to investigate the electrical properties of the self-sensing asphalt materials. CT scanning was then performed to evaluate their microstructure and the distribution of conductive additives in the materials. Furthermore, Marshall specimens with the optimal GP (0.68%) and varying SF contents (0.9%–1.1%) were compacted for 40–90 blows to obtain different air void volumes (VVs), as shown in **Fig. 2**. The electrical resistivity of these specimens with varying VVs was measured to characterise their electrical sensitivity to air void volume. Moreover, three-point bending (3PB) damage tests (see **Fig. 3**) were conducted to investigate their damage-monitoring performance. During the tests, the crack length and resistivity of beam specimens were recorded at the same time. Finally, the mechanical properties of self-sensing asphalt materials were studied by Marshall splitting tests.

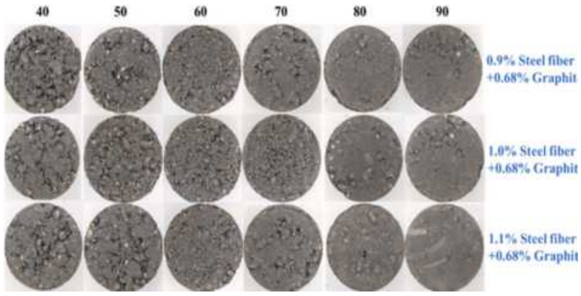

Fig. 2. Marshall specimens with different compaction times.

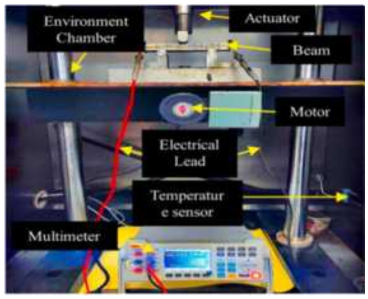

Fig. 3. Three-point bending (3PB) damage tests.

2 Major results and findings

A self-sensing asphalt material was developed with a combination of GP and SF. Its electrical resistivity can gradually change with the increasing content of conductive additives, which is critical for a wide sensing range and consistent sensing and precise control of the self-sensing asphalt materials conductivity. The self-sensing asphalt materials with GP of 0.23%, 0.45% or 0.68% and SF of 0.9% or 1.0% had an acceptable resistivity variability.

An efficient internal conductive network was constructed by the synergistic effect of GP (short-range contacts) and SF (long-range bridging). The self-sensing asphalt materials with GP of 0.68% and SF of 0.9-1.1% has excellent electrical and mechanical properties with an efficient internal conductive network.

The self-sensing asphalt materials exhibited a high electrical sensitivity to the change of the volume of air voids (**Fig. 4**), which is critical to accurately monitor the damage states of asphalt pavements.

The self-sensing asphalt materials had a gradual resistivity change due to the internal damage (**Fig. 5**), which indicates its excellent damage-monitoring performance.

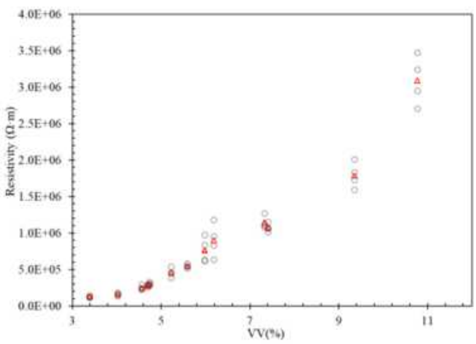

Fig. 4. Resistivity of specimens (0.9% SF + 0.68% GP) with different VVs.

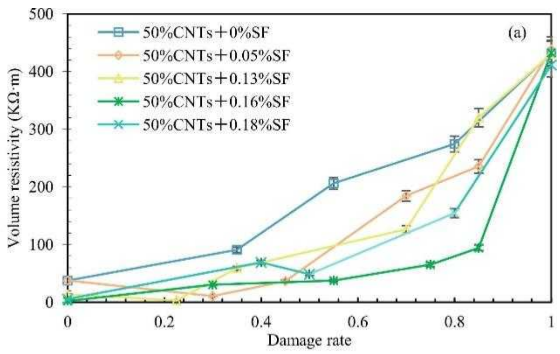

Fig. 5. Volume resistivity of specimens with different damage rates.

The self-sensing asphalt materials showed great mechanical properties (i.e., splitting strength) compared to the plain ones due to the reinforcing effect of conductive additives.

How to Update the Digital Twin? —A Fault Tree Risk Analysis for Pavement Infrastructure

Qiao Dong[1], and Ruiqi Li[2]

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Graphical abstract

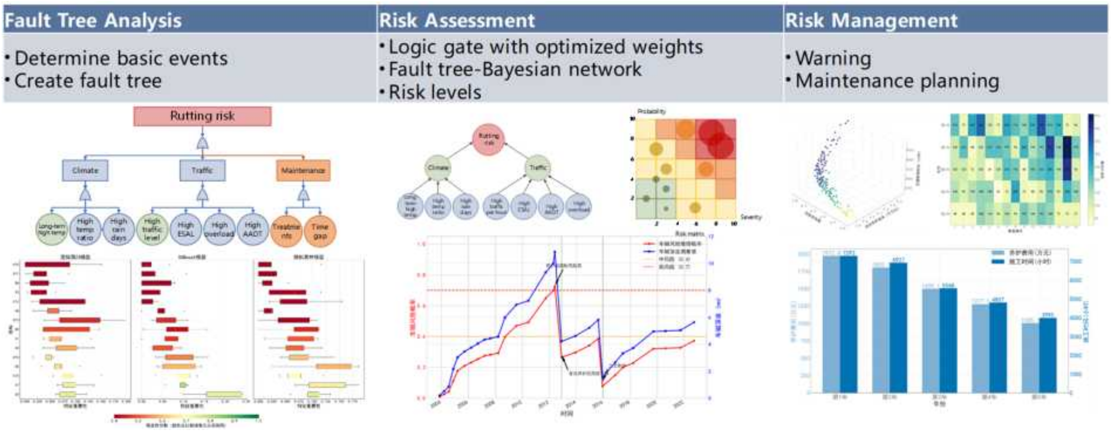

Figure 1 Graphical abstract

1 Objectives and Methodology

The research aims to develop a dynamic and flexible fault tree risk analysis framework for pavement infrastructure digital twins. A dynamic model for the fault tree top event failure probability is built using extended weighted logic gates. A multi-dimensional pavement risk classification system is developed and a multi-objective optimization model weighing maintenance cost, risk, and traffic impact is established.

2 Major results and findings

Table 1 Major Findings

Fault tress analysis	A fault tree modeling method for pavement performance evaluation is proposed, and machine learning algorithms were used to identify important features or base events.
Risk assessment	The dynamic update model of the top event failure probability is established. The fault tree is coupled with the Bayesian network to construct the dynamic probabilistic reasoning models, providing a quantification basis for risk evolution in complex environments. A multi - dimensional pavement risk classification standard is established based on a double evaluation system of risk matrix and risk priority number.
Risk Management	Agile response to and rapid disposal of risk events have been achieved. A multi-objective optimization model focusing on maintenance cost, risk level, and traffic impact has been constructed.

Intelligent Inspection and Digital Management of Airport Pavement

Xu Yang1
1 Chang'an University,Xian,China

Abstract:

针对机场道面传统养护面临的检测效率低、精度差、数据管理难及可视化程度弱等挑战，长安大学杨旭教授团队系统开展了机场道面智能检测与数字化管理技术研究。在表观病害智能检测方面，团队开发了基于卷积拓扑的像素级裂缝分割方法，识别精度达 92%，速度提升 30%；设计了 2D/3D 自适应融合算法，将复杂病害分割精度提升 6-9%；并实现了基于无人机和激光雷达的全天候高精度三维表面重建。在内部状况智能感知方面，构建了大规模多频探地雷达（GPR）数据库，基于深度学习实现了对脱空、松散、裂缝等多种内部隐蔽病害的智能识别、可视化与量化反演，并提出了内外联合的道面状况综合评价新方法。在数字化管理方面，基于 BIM 和 GIS 技术，开发了自动化病害建模方法和可视化“一张图”管理平台，打通了从数据采集、健康评价到三维可视化的全周期数字孪生管理链路。该系列技术成果已发表高水平论文 20 篇，授权或申请发明专利 17 项，获软件著作权 3 项，并成功应用于西北地区 14 个机场的建设与养护工程中，有力支撑了机场设施的智慧化运维。

Exploring the Application of Digital Twins in Infrastructure Engineering – Improving Asphalt Pavement Construction

Chonghui Wang,
Aston University, UK.

Abstract:

Digital Twin (DT) technology is rapidly reshaping infrastructure engineering by integrating real-time sensing, numerical modelling, and AI-driven analytics to create dynamic virtual replicas of physical assets. This presentation investigates how DT can enhance construction quality, sustainability, and operational efficiency in asphalt pavement engineering through the development of a cyber-physical paving model. Drawing on laboratory and field-based experiments using SmartRock sensors and discrete element modelling (DEM), the study demonstrates how DT enables real-time monitoring of compaction behavior, optimizes mixing and paving processes, and improves decision-making efficiency. The research further addresses the challenges of multi-scale data integration and proposes a hybrid modelling approach that links microscale aggregate interactions with macroscale pavement performance. Case studies from recent EPSRC- and DFG-funded projects will be presented to illustrate real-world applications and the transformative potential of DT in road infrastructure. The findings offer critical insights into how DT technology can advance the development of resilient and sustainable transport systems and inform future directions for its broader implementation in smart infrastructure.

Paralel Session C3 Summary:

The session discussion centered on the major challenges associated with applying Digital Twin (DT) technology in road infrastructure. Both speakers and attendees shared valuable insights and perspectives, summarized as follows:

- The current development of DT in road engineering primarily emphasizes the collection of field and on-site data to virtually represent the status of road infrastructure. However, it lacks advanced capabilities for in-depth analysis and predictive decision-making in road asset management.
- Significant challenges remain in real-time data sensing, acquisition, and transmission, particularly due to the large volume of data, the need for effective data fusion, and the complexity of processing to extract key information. Addressing these issues requires interdisciplinary collaboration across domains such as sensing technology, data science, and civil engineering.
- Incorporating physics-informed models into DT frameworks, especially when integrated with AI-driven predictive tools, is essential to enhance response times, improve predictive accuracy, and reduce system costs.
- One of the key unresolved challenges is ensuring timely updates and high-accuracy predictions in DT models based on real-time sensing data. This demands a deeper understanding of road engineering mechanisms and behaviors under various operational and environmental conditions.
- Developing and deploying a full-scale DT system requires substantial upfront investment in hardware (e.g., sensors, edge devices), software, and skilled personnel. For many agencies, particularly in developing regions, this can be a significant barrier.

Paralel Session C4

Topic: Leading International Experts Commentary on Transportation Infrastructure

Graduate Students Presentations (8min/presentation)

Host: Yao Zhang, Associate Professor, Yangzhou University, Hongwei Lin, Associate Professor, Beijing Jiaotong University

Experts: Ya Wei, Professor, Tsinghua University; Qingzhao Zhang, Associate Professor, Tongji University; Yanjun Qiu, Southwest Jiaotong University; Linbing Wang, University of Georgia

Speech:

Development of an Intelligent Detection System for Crown Voids and Air Bubbles in Tunnel Linings Based on Multi-Directional Ultrasonic Sensing

Linghui Kong, Tsinghua University

Research On Structural Design of Shield Tunnels under Deep Burial Depth and High Water Pressure

Siqi Yang, Hunan University

Multiscale Fracture Mechanics Corrosion Prediction Model of Concrete Based on Nano- and Microscale Parameters from SEM and AFM PF-QNM

Huifang Liu, University of Science and Technology Beijing

Research on Experimental Study and Analytical Theory of Stress Evolution Around a Tunnel in Reclaimed Unconsolidated Layers

Xinxin Yang, Hunan University

Preparation of Low Temperature Rapid Curing Self-Healing Microcapsules Based on Polythiol

Jiajia Sheng, University of Science and Technology Beijing

Reinforcement Mechanism and Design Method for Cracked Tunnels Based on Sprayed UHPC Technology

Tao Chen, Hunan University

A Physics-Informed Fuzzy Clustering Prediction Method: A Case Study on Vehicle Weight Identification Based on Pavement Vibration Signals

Songli Yang, University of Science and Technology Beijing

Study on Mechanical Behavior of Ultra High Performance Concrete(UHPC) Filled GFRP Tubular Arch

Zhenyuan Yang, Nanjing Tech University

Considering the Influence of the Constitutive Model for Asphalt Concrete and Thermal Expansion Property of Base Material on Pavement Response

Longqi Yan, Beijing University of Technology

Study on Creep Behavior and Prediction Models of Internal Curing UHPC

Weichen Fan, University of Science and Technology Beijing

Acoustic Emission-Based Statistical Modeling of Low-Temperature Damage in Steel Slag and Crumb Rubber Modified Asphalt Mixture

Tao Li, Inner Mongolia University of Technology

Experimental Testing and Analysis of Long-term Time-dependent Deformation of Prestressed Ultra-high Performance Concrete Beams

Changliang Sun, University of Science and Technology Beijing

Multiscale Modeling and Temperature Field Analysis of Asphalt Pavement

Jiahao Bai, University of Science and Technology Beijing

Data-Driven Inverse Analysis of Axle Loads and Surface Modulus in Asphalt Pavements Using Vibration Measurements

Fei Yang, University of Science and Technology Beijing

Paralel Session D3

Topic: Performance-Reated Material Properties of Asphalt Mixture Components

Chair: Haibo Ding, Associate Professor, Southwest Jiaotong University
Cochair: LeiLyu, Lecturer, Chang'an University

Introduction:

Each component of an asphalt mixture (e.g., asphalt binder, aggregate, recycled materials and additives) directly affects the performance of the asphalt mixture and asphalt pavement, including fractures, permanent deformation, aging and moisture. Different damage modes are induced by different mechanisms and/or under different environmental conditions, and the contribution of each component to resist different types of damage is different. Therefore, it is vital to accurately evaluate the effects of the fundamental properties of asphalt mixture components and the component interactions that are related to damage performance, which are critical to develop performance models for asphalt mixtures. The assessment of material properties becomes essential when recycled materials and/or additives are involved.

Speech:

Optimized asphalt mix design method based on viscoelastic properties.
Meng Ling, Beijing University of Civil Engineering and Architecture

Upscaling prediction of dynamic compression viscoelastic properties of asphalt mortar from asphalt mastic.
Derun Zhang, Huazhong University of Science and Technology

Application of corn straw biochar in pavement asphalt: Suppression of hazardous fume emissions and maintenance of rheological properties.
Yiming Li, Northeast Forestry University

Exploring the enhancement mechanisms of bio-oils and crumb rubber in asphalt binders.
Lei Lyu, Chang'an University

Precipitation and prediction of crystalline components in asphalt.
Haibo Ding, Southwest Jiaotong University

Optimized asphalt mix design method based on viscoelastic properties.

Meng Ling

Beijing University of Civil Engineering and Architecture

Abstract:

In this study, permanent deformation potential of different asphalt mixtures subjected to the same aging condition was assessed, based on viscoelastic characteristics from the dynamic modulus (DM) test. First it was shown that the HWTT and RLPD test results were not well correlated, which might be due to the differences in the boundary condition and the impacts of moisture damage and stripping in the HWTT. The analysis results suggested that the shape parameter (γ) of the DM master-curves could be utilized to assess the rutting resistance potential of the asphalt mixtures from the RLPD test, compared to other rheological parameters such as the inflection point frequency and β. The |E*| at the RLPD test condition was well correlated to the rutting performance compared to the asphalt mixture's rutting parameter |E*|/sinδ and the |E*| at the inflection point frequency. A novel rutting parameter (VERIndex) was developed to assess the rutting resistance potential of the asphalt mixtures, which simultaneously accounts for the |E*| and slope of the DM master-curves. Thereafter, the cracking and rutting performance thresholds were proposed, and, correspondingly used in the performance space diagram to aid with implementing the balanced mix design approach using the viscoelastic characteristics of asphalt mixtures.

Upscaling prediction of dynamic compression viscoelastic properties of asphalt mortar from asphalt mastic.

Derun Zhang,
Huazhong University of Science and Technology

Abstract:

Simulating the viscoelastic behavior of asphalt materials at different scales and predicting the dynamic viscoelastic properties of "large-scale" asphalt materials through the "small-scale" is crucial for the reliable digital design of asphalt mixture. This paper proposed a new upscaling simulation approach for the prediction of dynamic compressive viscoelastic properties (i.e. dynamic compressive modulus and phase angle) of asphalt mortar based on those of the asphalt mastic. In this new approach, an asphalt mastic design method was first developed, by which the properties of asphalt mastic can match with those of asphalt mortar. The dynamic compressive modulus test was then conducted to obtain the dynamic compressive modulus and phase angle of the asphalt mastic. The upscaling simulation of the dynamic compressive viscoelastic behavior from the asphalt mastic scale to the asphalt mortar scale was subsequently carried out with the aid of two-dimensional random aggregate virtual model, which enables the prediction of dynamic compressive viscoelastic properties of the asphalt mortar. Finally, feasibility of the new approach was systemically evaluated. Consistency between the predicted simulation results and the experimental test results verified the feasibility of the new approach in accurately predicting the dynamic compressive viscoelastic properties from asphalt mastic to asphalt mortar.

Application of corn straw biochar in pavement asphalt: Suppression of hazardous fume emissions and maintenance of rheological properties.

Yiming Li
Northeast Forestry University

Abstract:

The emission of asphalt fumes during pavement construction and the improper disposal of corn straw pose significant environmental challenges. This study characterizes the physicochemical properties of corn straw biochar and evaluates its effects on volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) in asphalt fumes at 140℃, 150℃, and 160℃, as well as the total carcinogenic toxicity (TCT) of 16 priority PAHs. Additionally, the impact of biochar on asphalt binder performance was investigated. The results show that corn straw biochar possesses a well-developed pore structure, abundant functional groups, and a high surface area. Biochar significantly reduced the concentration and toxicity of VOCs and PAHs, with optimal effects observed at a 3 % biochar content. Furthermore, biochar improved the high and medium temperature performance of asphalt binders while slightly impairing low-temperature properties. At 2 % biochar content, asphalt binder performance was balanced across all temperatures, with reduced toxicity of asphalt fumes. The incorporation of corn straw biochar as an additive in asphalt exhibits the potential to enhance high-temperature stability of the asphalt and reduce smoke emissions, thereby offering a novel approach for promoting the high-value utilization of agricultural waste.

Exploring the enhancement mechanisms of bio-oils and crumb rubber in asphalt binders.

Lei Lyu
Chang'an University

Abstract:

Waste bio-oils and scrap tires as industrial waste streams have caused serious health risks and environmental burdens. This study aims to provide a method for hybrid reuse of both wastes to create bio-modified rubberized asphalt and unravel the underlying modification mechanisms using microscopy and chemo-rheological investigations. This hybrid use mitigates some of the challenges faced when using one of the waste streams such as storage stability. The chemical analysis suggests the deoxidizing and devulcanizing effects of bio-modification on the crumb rubber. Thermal analysis shows the bio-modification on crumb rubber decreases the glass transition temperature of the asphalt binder, thereby enhancing the low-temperature properties as also shown in the rheology through the Glover-Rowe parameter. Environmental scanning electron microscopy demonstrates that crumb rubber alone mainly acts as a particle filler, while phase separation is mitigated after bio-modification. This contributes to the different deformation resistance mechanisms as shown in multiple stress creep and recovery test. The decreased length and stiffness difference of catana domains were observed in the asphalt binder after the addition of crumb rubber and bio-oils using atomic force microscopy. Rheological analysis shows the positive effects of bio-modified asphalt rubber i.e. a more elastic response at high temperatures and a more viscous response at low temperatures. The outcome of this study provides insight into converting the two waste materials (bio-oils and crumb rubber) into valuable resources for pavement construction to ensure the sustainability of transportation environments.

Precipitation and prediction of crystalline components in asphalt.

Haibo Ding
Southwest Jiaotong University

Abstract:

Considering asphalt as a mixed system composed of multiple solid and liquid phases based on the principle of phase equilibrium and regular solution theory, in this paper, the activity coefficient was used to describe the non-ideality of solid and liquid phases. According to the phase equilibrium equation, mass equilibrium equation, and normalization equation, the solid–liquid fraction under the equilibrium condition was calculated, and then the precipitation temperature of paraffin wax in asphalt and the precipitation amount at each temperature were determined. The gas chromatography-mass spectrometry experiment was conducted to measure the paraffinic, naphthenic and aromatic distribution of the asphalt as the input parameter of the prediction model. After the calculation results of the wax precipitation temperature (WPT) and wax precipitation curve (WPC) were compared with measured values acquired from experimental methods (viscosity method, Fourier-transform infrared spectroscopy (FTIR) method), it was found that the trend of WPC is approximately similar, but the WPT of the theoretical model was significantly higher than that of FTIR. The authors believe that this was caused by the overestimation of the thermodynamic properties of the aromatic components. After reducing the melting point and enthalpy of the aromatic components to a certain extent, satisfactory results were obtained.

Paralel Session D4

Topic: Environmental-Friendly Pavement Materials

Chair: Yue Xiao, Professor, Chang' an University
Cochair: Quantao Liu, Professor, Wuhan University of Technolgy; Jiuguang Geng, Associate Professor, Chang'an University

Introduction:

当前，我国交通基础设施建设正处于从“规模扩张”向质量提升和绿色低碳转型的关键阶段。随着“双碳”目标的深入推进与生态文明建设的深化，传统道路建设模式面临严峻挑战：一方面，公路建设与养护消耗大量天然砂石、沥青等资源，每年产生数百万吨建筑垃圾；另一方面，常规筑路材料生产过程能耗高、污染大，加剧了生态环境压力。同时，城市交通噪声污染、公路沿线生态退化等问题日益凸显，对居民生活质量和生态系统健康构成持续威胁。

在此背景下，“环境友好路面”作为融合资源循环、节能减排和生态协调理念的综合解决方案，已成为行业创新前沿。

在全球气候变化和城市可持续发展议题日益紧迫的今天，道路基础设施的环保转型已成为不可忽视的重要议题。本次会议以“环境友好路面”为主题，旨在深入探讨绿色道路材料、生态铺装技术、低碳施工工艺与智能运维模式，为城市建设和交通运输领域的可持续发展提供创新思路和解决方案。

当前，传统路面在能耗高、雨水径流污染等方面暴露出诸多环境问题。为应对这些挑战，越来越多的科研机构、企业与政府部门正积极推动透水性路面、可再生材料应用、低噪音结构与碳足迹评估体系的研究与实践。

本次会议汇聚了来自道路工程、材料科学等多个领域的专家学者与行业代表，将通过专题报告，探索环境友好路面的新趋势、新机遇与现实挑战。我们希望借助这一平台，激发跨界协作与技术创新，为构建低碳、宜居、韧性的城市环境贡献智慧与力量。

Speech:

Mechanisms of Antioxidant Intercalated LDHs on Enhancement of thermal Oxidative and UV Aging Resistances of Asphalt binder

Quantao Liu, Shuaochao Chen, and Huan Wang, State Key Laboratory of Silicate Materials for Architectures

Quantification and deodorization of emissions from high content rubber modified asphalt

Naipeng Tang, School of Civil Engineering, Chongqing Jiaotong University

Inhibitory mechanism of zinc stearate on the sulfidation gases from crumb rubber modified asphalt

Jiuguang Geng, Wenhui Zhao, School of Materials Science and Engineering, Chang'an University

Micro-Mesoporous Design and Modification of Molecular Sieve for Emission Reduction of Asphalt VOCs

CHANG Xiwen, XIAO Yue, School of Materials Science and Engineering, Chang'an University

Research on Data-Driven Decision-Making Technology for Green Pavement Maintenance and Quantitative Assessment of Carbon Emissions

YI Mingwei, XIAO Yue , PAN Zongjun, CHANG Rong, YI Xiaoming, RoadMainT Co., Ltd.,

Mechanisms of Antioxidant Intercalated LDHs on Enhancement of thermal Oxidative and UV Aging Resistances of Asphalt binder

Quantao Liu, Shuaochao Chen, and Huan Wang
State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, China, liuqt@whut.edu.cn.

1 Objectives of this research

Asphalt aging seriously shortens the service life of asphalt pavement, and improving the anti-aging performance of asphalt is of great significance for prolonging the service life of asphalt pavement. In order to improve the anti-aging performance of asphalt, scholars at home and abroad have carried out a lot of research work. The main measures taken are to add anti-aging materials such as antioxidants, UV absorbers, UV blockers into asphalt, improving its anti-aging performance by blocking the aging reaction path of asphalt or blocking the penetration of light, heat and oxygen into the asphalt. However, these anti-aging materials are all individual countermeasures for thermal oxygen aging or UV aging, and can't solve the problem of thermal-oxidative aging and ultraviolet aging of asphalt pavement simultaneously. The construction of long-life pavement has put forward higher requirements for the comprehensive anti-aging performance of asphalt, and it is urgent to develop more advanced and effective thermal oxygen aging and ultraviolet aging synergistic prevention technology for road asphalt. This study prepared a new type of anti-aging materials (LDHs-1222) with both UV light shielding and free radical trapping functions by intercalating organic antioxidant 1222 into the interlayers of supramolecular ultraviolet barrier material LDHs. From the two aspects of stopping the free radical chain reaction of asphalt and blocking the penetration of UV light into asphalt, they synergistically improved the thermal oxygen aging and anti UV aging properties of asphalt. This research revealed the wokring mechanism of the new type of anti-ageing material, laying a theoretical and application foundation for the synthesis control and anti-aging performance improvement of asphalt anti-aging materials.

2 Methodology and main research work

LDHs-1222 with good free radical trapping ability and UV shielding performance were prepared using structural reconstruction method, shown in Figure 1. By comparing with common anti-aging agents, the synergistic effect of LDHs-1222 on asphalt thermal oxygen resistance and ultraviolet aging resistance was revealed. Based on the free radical capture theory, the influence of LDHs on the aging process and aging products of asphalt was explored, and the interaction mechanism between LDHs-1222 and asphalt during thermal oxidative aging was revealed. By studying the effects of LDHs-1222 on the UV light transmittance, UV aging depth, and diffusion rate of aged asphalt, the mechanism by which LDHs-1222 enhance the UV aging resistance of asphalt was revealed.

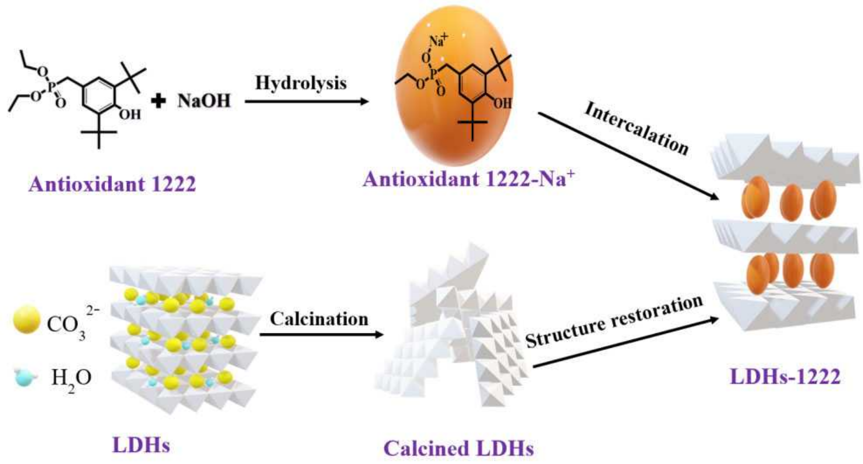

Figure 1 Schematic diagram of synthesis of LDHs-1222

3 Major findings

The LDHs intercalated with antioxidants have good free radical capture ability and UV shielding performance, and have little effect on the physical and rheological properties of asphalt. After being added to asphalt, the resistance to thermal oxygen aging and UV aging of asphalt is improved simultaneously. The LDHs-1222 modified asphalt with a 4% dosage has the best resistance to thermal oxygen and UV aging. The particle uniformity, distribution uniformity, and compatibility with asphalt of LDHs-1222 are better than those of LDHs, which helps them to exert their anti-aging effect; LDHs-1222 inhibit the formation of functional groups with additive condensation properties such as C ≡ C triple bonds, C ≡ N triple bonds, accumulated dienes, and carbonyls during the aging process of asphalt. The captured active molecules such as polycyclic alkanes, nitrogen-containing heteroaromatic hydrocarbons, and long-chain aromatic hydrocarbons react with antioxidants to form ether bonds, hindering the thermal oxidative aging process of asphalt. LDHs-1222 modified asphalt film has excellent UV shielding performance, and its UV light penetration depth is 41.17% lower than that of base asphalt, improving the UV aging resistance of shallow asphalt. Within the thickness of asphalt directly irradiated by UV light (<10 μm) The carbonyl index of LDHs-1222 modified asphalt decreased by 26.4% compared to the base asphalt; In the area of asphalt aging diffusion (≥ 10 μm) The LDHs-1222 plate-like structure and the ability to capture free radicals can also inhibit the internal diffusion of aged asphalt molecules, significantly reducing the diffusion rate of aged asphalt molecules, thereby improving the UV aging resistance of asphalt.

4 Conclusions

New anti-aging materials with good free radical capture ability and UV shielding performance can be prepared by intercalating antioxidants into the LDHs layer. The anti-aging performance of asphalt can be improved from the two aspects of terminating the free radical chain reaction of asphalt and blocking the penetration of UV light into asphalt and the penetration of the aged asphalt at the surface (Figure 2).

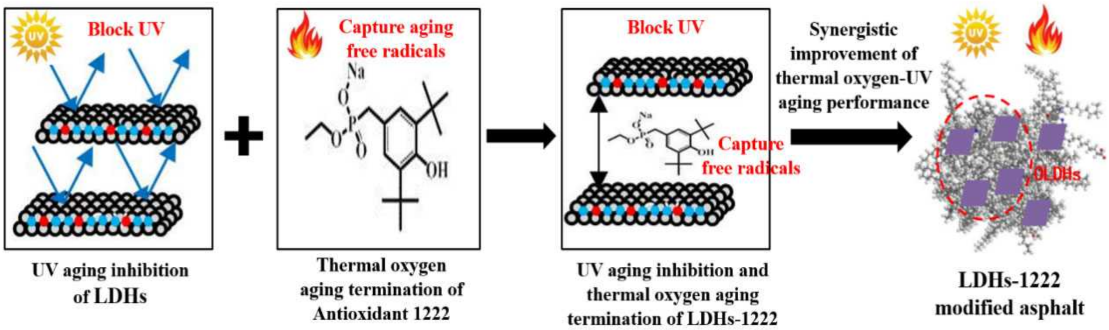

Figure 2 The working principle of LDHs-1222

Quantification and deodorization of emissions from high content rubber modified asphalt

Naipeng Tang [1, 2]

[1] School of Civil Engineering, Chongqing Jiaotong University, Chongqing, 400074, China;

[2] National & Local Joint Engineering Research Center of Transportation and Civil Engineering Materials, Chongqing Jiaotong University, Chongqing, 400074, China.

1 Objectives of this research

Rubber asphalt has excellent road performance, but due to its strong odor during construction, it is difficult to promote and use. In addition, rubber asphalt smoke affects the environment and health (Wei et al. 2024). CRMA with a crumb rubber content exceeding 25% is typically classified as high content rubber modified asphalt (HCRMA)(Zhu et al. 2022). HCRMA facilitates higher waste tires recycling rates and further enhances the pavement performance of rubber-modified asphalt. But it further exacerbates the problem of pollutant emissions. Based on this, this study first introduces the sampling and quantitative measurement methods of high content rubber asphalt emissions, and then conducts research on deodorization of high content rubber asphalt.

2 Methodology and main research work

2.1 Methodology

Indoor sampling test is an important test method for reflecting asphalt emissions. The indoor smoke test used in this study involves sealing asphalt in a 2L reaction kettle, controlling the test temperature through a constant temperature device, and then using an adsorption medium to adsorb the smoke emissions. Finally, GC-MS analysis is used to analyze the characteristics of smoke emissions, and indoor tests are used to evaluate and control the emissions in actual production and construction. The detailed experimental process is shown in the Figure. 1. The quantitative evaluation method for inorganic gaseous emissions is shown in the Figure. 2. In environmental science, the evaluation of odorous gases is often based on the olfactory threshold, which can be used to quantify the odorous intensity. The olfactory threshold is the minimum concentration of a gas that can cause a detectable olfactory stimulus, which is the lowest concentration at which the human olfactory system can perceive the odor of the gas.

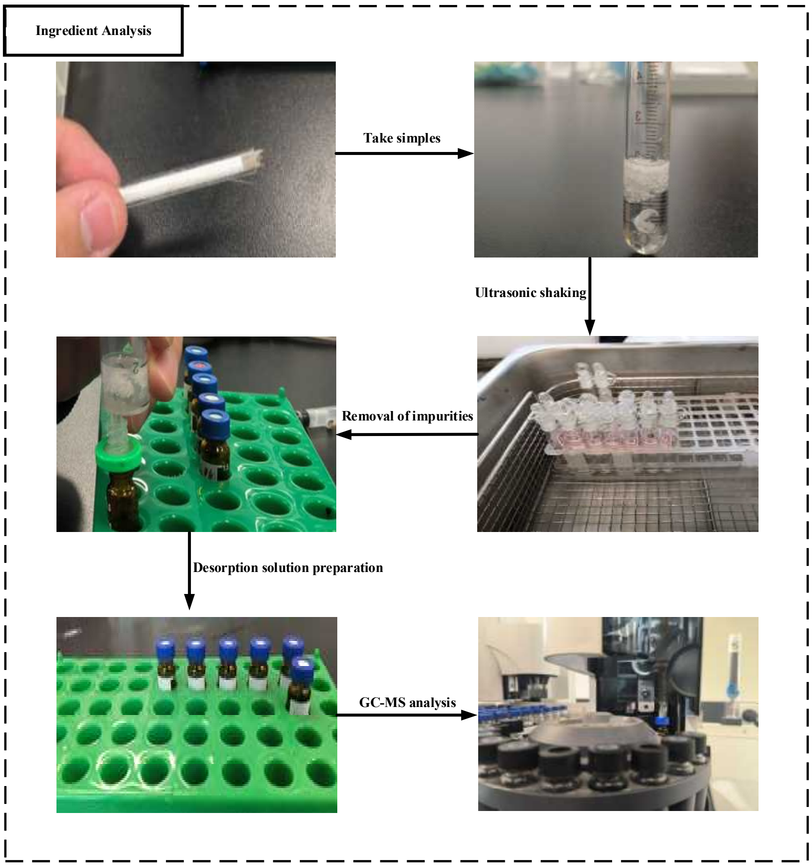

Figure. 1 The GC-MS sample preparation procedure

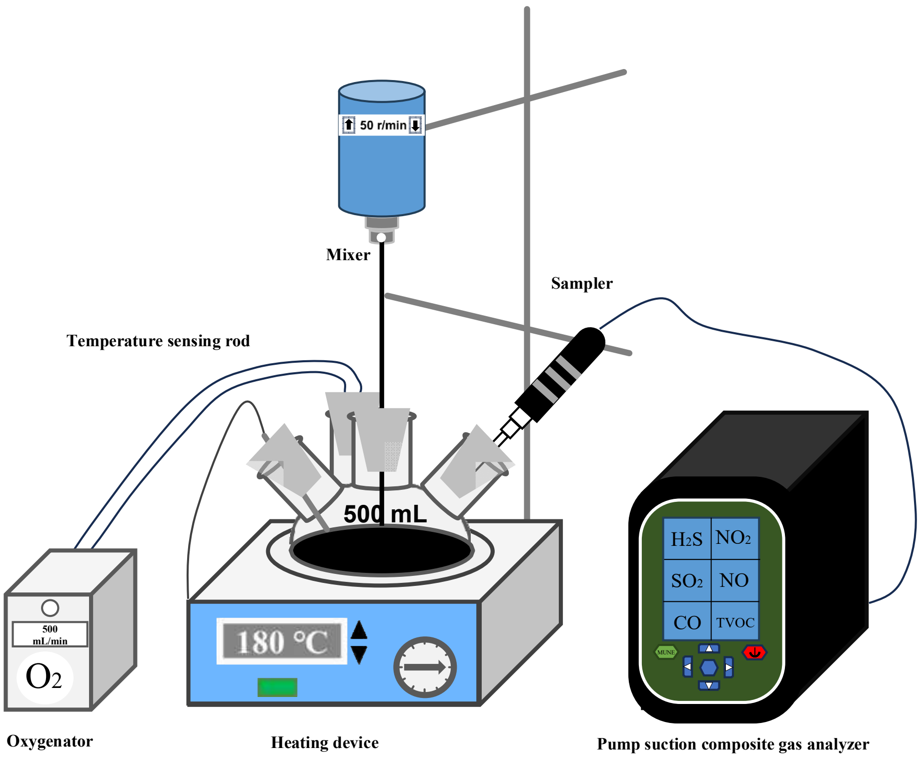

Figure. 2 The collection device and a portable gas analyzer

2.2 Main research work

Indoor sampling test is an important test method for reflecting asphalt emissions. The indoor smoke test used in this study involves sealing asphalt in a 2L reaction kettle, controlling the test temperature through a constant temperature device, and then using an adsorption medium to adsorb the smoke emissions. Finally, GC-MS analysis is used to analyze the characteristics of smoke emissions, and indoor tests are used to evaluate and control the emissions in actual production and construction. When conducting indoor smoke tests, there are many factors that affect the test, mainly including sampling method, stirring rate, stirring blade width, etc. Adsorption medium and sampling time can also affect the qualitative and quantitative analysis of asphalt smoke.

Therefore, this study explores various influencing factors, adjusts experimental instrument parameters based on collected data, and provides specific experimental steps and parameters for the formulation of subsequent experimental procedures. This study designed four different operating conditions. The research results indicate that under static conditions, the total PAHs emissions are relatively low. Under stirring conditions, the VOCs emissions in operating conditions 2 and 3 significantly increase, and stirring can significantly increase the emissions of n-alkanes. In indoor smoke tests, mechanical stirring is not only closer to the state of asphalt in actual use, but also can stimulate the volatilization and emission of a large amount of organic matter. The large amount of organic matter volatilization can effectively improve the analysis accuracy of GC-MS. The PAH emissions of blades with a width of 6 cm and 9 cm are similar under different widths, and the impact of stirring blades on PAH emissions is relatively small The emissions absorbed by activated carbon adsorption tubes are significantly smaller than those absorbed by XAD-2 resin The size of the reaction vessel mainly affects the migration process of flue gas during the release extraction process. A high headspace volume will cause significant gas loss during the extraction process. The smaller the headspace volume, the faster the gas is released into the extraction process, and the smaller the experimental error. Therefore, it is recommended to use a 500ml reaction vessel for standardized experiments Internal standard method can more accurately determine emission results. Design a standard process based on the research results obtained through the entire sampling analysis standard process (Figure. 3). Afterwards, headspace emission tests were conducted on AR30, AR40, and AR50. The emissions of rubber powder modified asphalt were significantly higher than those of SBS modified asphalt. With the increase of rubber powder content, the emissions of rubber powder modified asphalt gradually increased. When the content reached 50%, the emissions increased significantly, and the emission characteristics also changed significantly. The proportion of naphthalene emissions increased by three times. For characteristic emissions in rubber, such as benzothiazole, quinoline, and phenylenediamine, with the increase of rubber powder content, the emissions also increased to a certain extent, among which benzothiazole had the highest emissions. To reduce the emission of gaseous pollutants, especially odorous gases from HCRMA, montmorillonite, attapulgite, and illite were added as emission reduction agents to HCRMA. Gas chromatography-mass spectrometry (GC-MS) and a portable gas analyzer were used to quantify the emission reduction effects of organic and inorganic compounds. The deodorization effect of HCRMA on organic and inorganic emissions was evaluated in detail. Further research was conducted on the emission reduction mechanism of emission reduction agents and their impact on the rheological properties of HCRMA. This study aims to develop an efficient emission reduction agent to promote the development and application of HCRMA materials. The research results indicate that montmorillonite effectively reduces the concentration of organic-inorganic emissions from high content rubber asphalt, and has the best inhibitory effect on odor substances. Partial research results are shown in the Figure. 4 and Figure. 5.

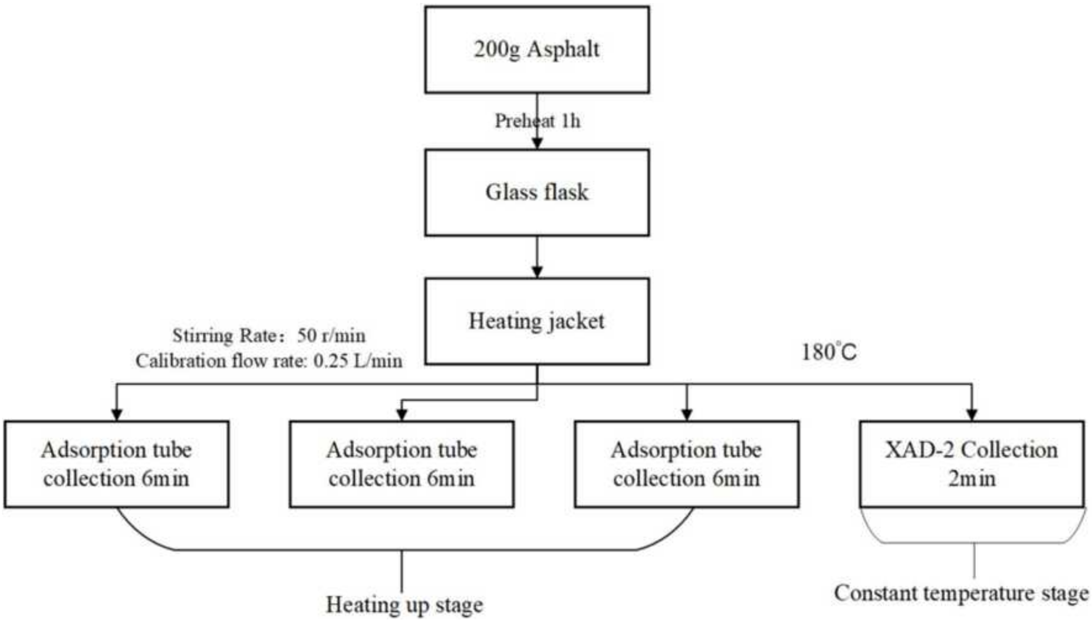

Figure. 3 Asphalt emissions collection process

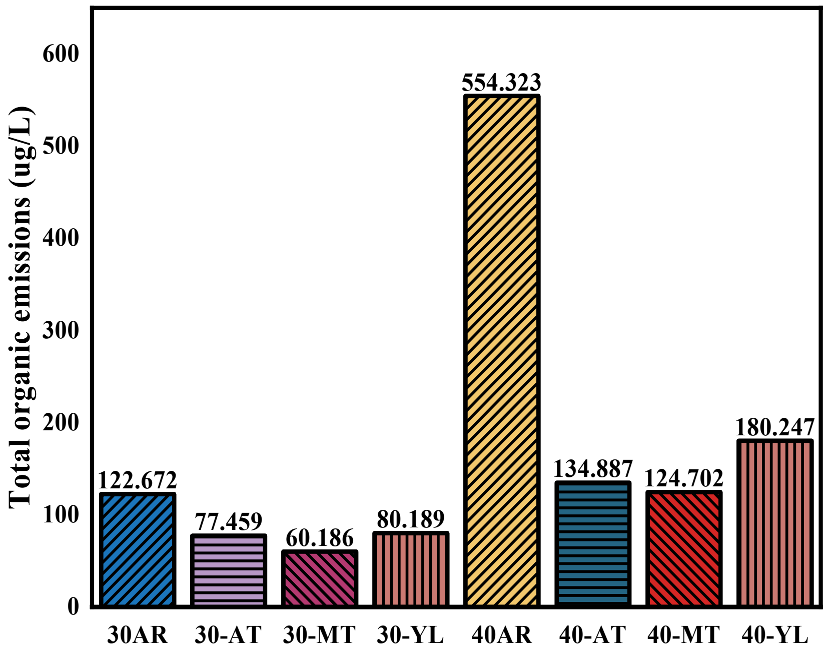

Figure. 4 The total organic emissions of 30AR, 40AR and ER-HCRMAs.

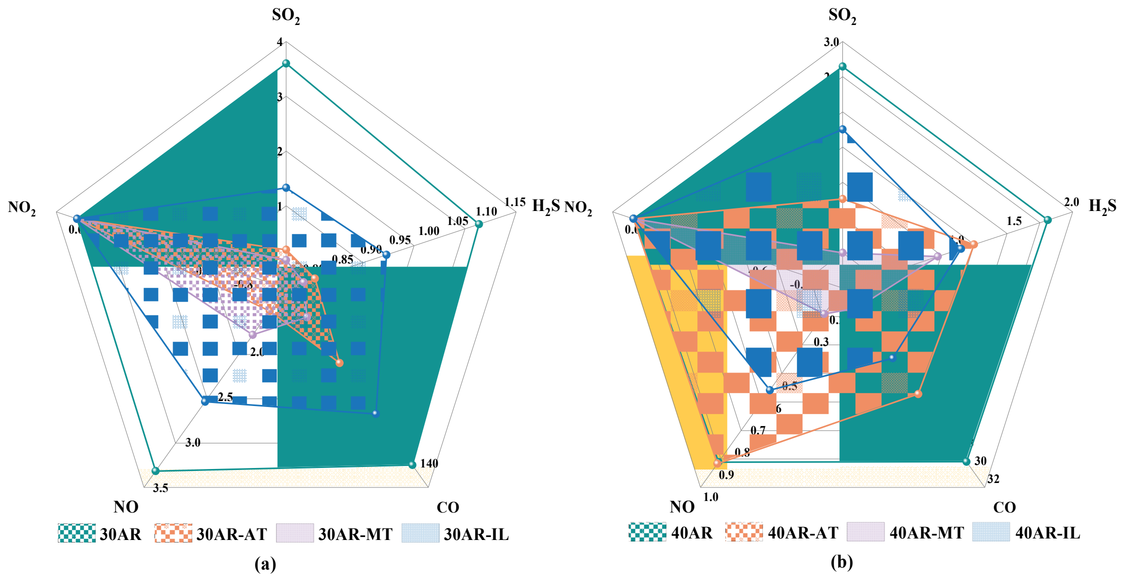

Figure. 5 The average of the inorganic emission concentration data points, (a)30AR series, (b) 40AR series

Table 3 Odor emission rate and odor contribution of inorganic emissions for 30AR, 40AR and ER-HCRMAs

Odorant gas	30AR		30AR AT		30AR MT		30AR IL	
	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)
H_2S	904.47	98.69	666.67	99.90	650.40	100.00	770.32	99.42
SO_2	12	1.30	0.66	0.10	0.03	0.00	4.4309	0.57
Total	916.47	100.00	667.33	100.00	650.43	100.00	774.75	100.00
Odorant gas	40AR		40AR AT		40AR MT		40AR IL	
	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)	Odor emission rate (min^{-1})	Odor contribution (%)
H_2S	1485.77	99.41	867.88	99.70	689.02	100.00	857.72	99.32
SO_2	8.813	0.58	2.54	0.29	0.00	0.00	5.83	0.67
Total	1494.58	100.00	870.42	100.00	689.02	100.00	863.56	100.00

3 Major findings

(1) The emission reduction effect of montmorillonite on organic emissions is superior to that of illite and attapulgite. The total organic emissions reduction rates of attapulgite, montmorillonite, and illite for 30AR are 36.89%, 50.82%, and 34.42%, respectively, and for 40AR are 75.81%, 77.62%, and 67.51%, respectively. Montmorillonite has the best deodorization effect on organic gases, with inhibition rates of 49.07% and 73.30% of 30AR and 40AR respectively.

(2) Montmorillonite has a better emission reduction rate and deodorization effect on inorganic gases than illite and attapulgite except for NO emission from 30AR. The

deodorization effect of montmorillonite, attapulgite and illite for 30AR is 28.67%, 27.18% and 15.46%, respectively. The deodorization effect of montmorillonite, attapulgite and illite for 40AR is 53.90%, 40.79% and 42.22%, respectively.

(3) Montmorillonite exhibited superior pore distribution and structural characteristics compared to attapulgite and illite. Furthermore, it demonstrated excellent emission reduction and odor deodorization properties. Based on the above conclusions, montmorillonite is recommended as an efficient emission reduction agent for HCRMA in road construction.

(4) The incorporation of montmorillonite can enhance the rheological and rutting resistance of HCRMA and improve its elasticity. Although it has a negative impact on the low-temperature performance and fatigue resistance of HCRMA, the low-temperature and fatigue properties of HCRMA still maintain at a good level. It can be concluded that the addition of montmorillonite has a relatively minor effect on the overall performance of HCRMA.

Inhibitory mechanism of zinc stearate on the sulfidation gases from crumb rubber modified asphalt

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Graphical abstract

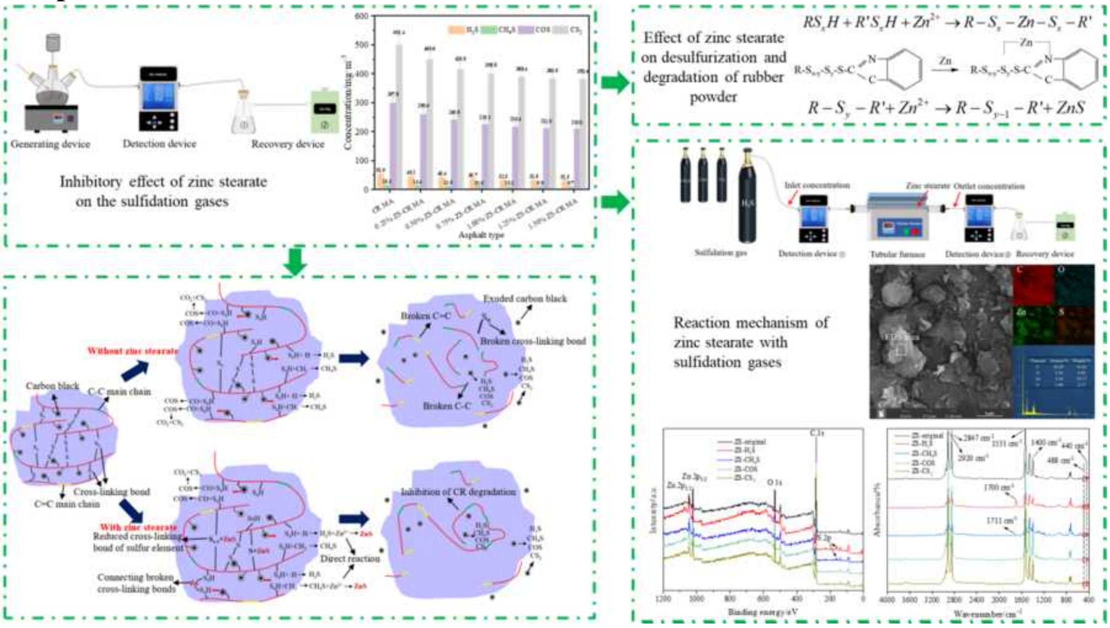

Figure 1 Graphical abstract

1 Objectives and Methodology

The utilization of crumb rubber modified asphalt (CR MA) in construction processes releases odor sulfidation gases, posing serious risks to the environment and construction workers. Consequently, effective measures to manage sulfidation gases from CR MA are imperative. Rubber vulcanization activators not only enhance the activation of the vulcanization reaction but also improve the cross-linking density and heat resistance of vulcanized rubber. In this paper, based on the concomitant mechanisms of sulfidation gases generation, rubber powder desulfurization, and degradation in CR MA, the inhibitory effect of rubber vulcanization active agent zinc stearate on the release of sulfidation gas (H_2S, CH_4S, COS, and CS_2) were investigated by gas analyzer. Toluene insoluble and potentiometric titration were used to reveal the effect of zinc stearate on the degree of desulfurization and degradation of crumb rubber in asphalt. Additionally, the reaction mechanism of zinc stearate with sulfidation gases was also studied using scanning electron microscope, X-ray photoelectron spectroscopy, and infrared spectroscopy.

2 Major results and findings

The results indicate that zinc stearate can effectively reduce the concentration of H_2S, CH_4S, COS, and CS_2 released by CR MA. Specifically, with a zinc stearate content of 1.5%, the concentrations of these gases were reduced by 39.69%, 36.60%, 29.48%, and 23.93%, respectively. Furthermore, the addition of zinc stearate also reduced the release of CH_2O, NH_3, CH_4, H_2, CO, and volatile organic compounds. Zinc stearate inhibited the desulfurization and degradation of crumb rubber in asphalt, and consequently reducing the concentration of sulfidation gases. Moreover, the reaction of zinc stearate with H_2S and CH_4S led to the formation of ZnS.

Table 1 Table and Figure name

Figure 1	Sulfidation gas concentration of CR MA versus zinc stearate content
Figure 2	Inhibition of zinc stearate on the volatilization of other small molecule gases and VOCs
Figure 3	Effect of zinc stearate on the desulfurization degree of crumb rubber in CR MA
Figure 4	Effect of zinc stearate on the degradation degree of crumb rubber in CR MA
Figure 5	Removal efficiency of zinc stearate on sulfidation gases
Figure 6	Effect of sulfidation gases on the microstructure of zinc stearate
Figure 7	Effect of sulfidation gases on chemical valence of zinc stearate
Figure 8	Effect of sulfidation gases on the functional groups structure of zinc stearate

Micro-Mesoporous Design and Modification of Molecular Sieve for Emission Reduction of Asphalt VOCs

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1 Objectives of this research

Due to the continuous high temperature in the construction process, asphalt materials continue to emit pollution to the environment 错误!未找到引用源。. Molecular sieves are used for reducing asphalt VOCs due to their porous structure 错误!未找到引用源。. However, since the microporous structure of molecular sieves cannot absorb large-sized VOCs 错误!未找到引用源。. Changing pore width distribution through alkali treatment can reduce more types of VOCs 错误!未找到引用源。. In addition, metal loading on molecular sieves has been proved to enhance adsorption capacity of p-xylene 错误!未找到引用源。. Therefore, surface modification by metal loading is explored to analyze emission reduction efficiency on asphalt VOCs.

2 Methodology and main research work

This study carried out the optimized design of ZSM-5 molecular sieve and emission reduction efficiency. Firstly, micro-mesoporous structure was constructed. Then, surface modification was carried out by loading Cu/Fe to improve reduction efficiency on highly toxic benzene series VOCs.

Alkali-treatment was been used to design the pore structure of molecular sieves by destroying Si in the skeleton. In this experiment, 9 types of micro-mesoporous molecular sieves were obtained by NaOH treatment on 3 types of ZSM-5 with 3 types of Si/Al ratios, which are named as 50-1, 50-2, 50-3, 600-1, 600-2, 600-3, 1000-1, 1000-2, 1000-3. Two micro-mesoporous ZSM-5 with the best emission reduction effect were loaded by Cu/Fe, attaining 600-3Cu, 600-3Fe, 1000-1Cu and 1000-1Fe. Then, the designed ZSM-5 molecular sieves will be incorporated into 70# matrix asphalt as additives with 2% dosage to prepare molecular sieve modified asphalt.

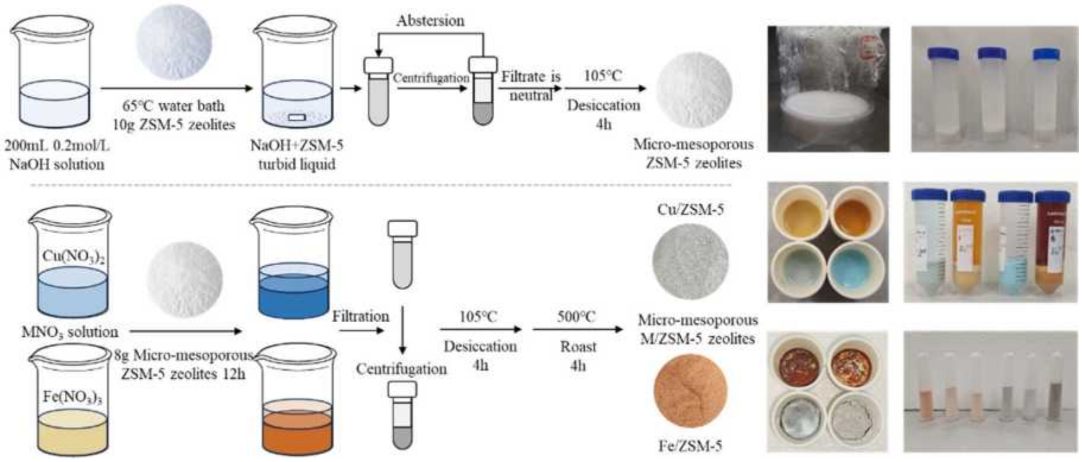

Figure 4: Synthesis of micro-mesoporous ZSM-5 and M/ZSM-5 molecular sieves

3 Major findings

3.1 Emission reduction efficiency of designed micro-mesoporous ZSM-5 molecular sieves

Quantitative calculation of VOCs was performed based on the fingerprint component database. The VOCs volatile factors and reduction efficiency compared as Figure 5. The data showed that volatile factors fluctuate in the range of 1.8-2.5 μg/g. The volatile factor of benzene series in the matrix asphalt is 0.05 μg/g, while in the five designed micro-mesoporous ZSM-5 molecular sieves modified asphalt is greater than 0.4 μg/g. The abnormal volatilization of benzene series greatly affects the overall emission reduction efficiency.

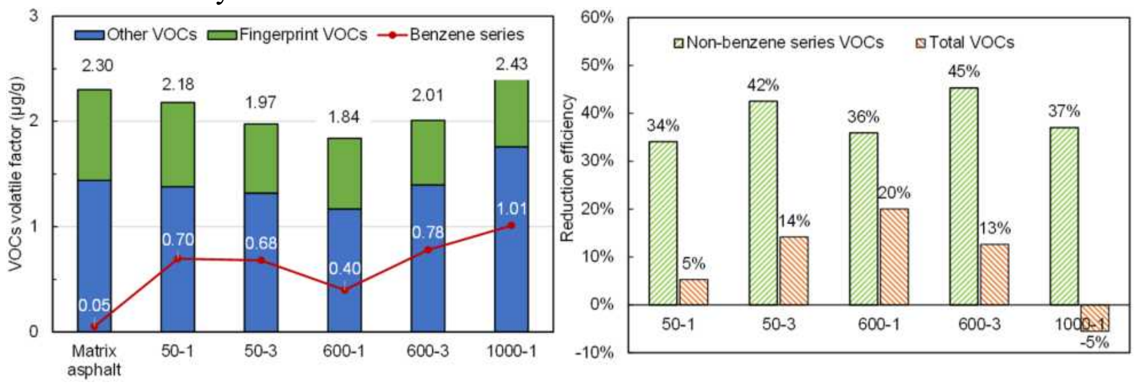

Figure 5: VOCs volatile factors and reduction efficiency of micro-mesoporous ZSM-5 modified asphalt

"Total VOCs" data show that 600-1 has the highest emission reduction efficiency, about 20%. "Non-benzene series" data show that the five molecular sieves can among reduce emissions more than 30%, of which 600-3 is the highest 45%. It indicates that designed micro-mesoporous ZSM-5 has excellent physical adsorption capacity for non-benzene series VOCs.

Table 4: Reduction efficiency of micro-mesoporous molecular sieve on VOCs with Top 20 peak area

Time	VOCs	Molecular formula	50-1	50-3	600-1	600-3	1000-1	Average
7.9696	1-Heptene	C_7H_{14}	61%	56%	46%	62%	63%	58%
8.2637	2-Heptene, (E)-	C_7H_{14}	60%	55%	47%	60%	63%	57%
11.1127	1-Heptene, 2,6-dimethyl-	C_9H_{18}	60%	54%	44%	56%	65%	56%
7.2403	Cyclopentene, 1-methyl-	C_6H_{10}	61%	59%	50%	47%	54%	54%
7.9227	1-Hexene, 2-methyl-	C_7H_{14}	58%	55%	40%	56%	58%	53%
5.9614	1-Pentene, 2-methyl-	C_6H_{12}	60%	50%	40%	60%	56%	53%
6.2869	2-Pentene, 4-methyl-, (E)-	C_6H_{12}	52%	51%	43%	62%	54%	53%
5.3494	1-Hexene	C_6H_{12}	59%	45%	39%	59%	57%	52%
7.4613	1-Hexene, 4-methyl-	C_7H_{14}	51%	47%	37%	56%	59%	50%
4.0987	Pentane	C_5H_{12}	52%	37%	42%	52%	50%	47%
6.0594	n-Hexane	C_6H_{14}	37%	39%	31%	48%	42%	39%
9.4013	Heptane, 2-methyl-	C_8H_{18}	35%	39%	35%	43%	38%	38%
8.0715	Heptane	C_7H_{16}	28%	37%	33%	41%	37%	35%
5.4797	Pentane, 2-methyl-	C_6H_{14}	14%	33%	30%	49%	42%	33%
10.0704	Octane	C_8H_{18}	30%	35%	36%	34%	27%	33%
7.5868	Hexane, 3-methyl-	C_7H_{16}	-19%	23%	26%	31%	28%	18%
9.3134	1-Heptene, 4-methyl-	C_8H_{16}	-14%	21%	27%	26%	14%	15%
7.3953	Hexane, 2-methyl-	C_7H_{16}	-61%	13%	22%	21%	12%	1%
8.6853	Cyclohexane, methyl-	C_7H_{14}	-46%	13%	18%	10%	3%	-1%
9.914	Toluene	C_7H_8	-378%	-241%	-108%	-260%	-346%	-267%

Reduction efficiency of designed micro-mesoporous ZSM-5 on single VOC were compared in Table 4. It lists main asphalt VOCs by average emission reduction efficiency from high to low. The 20 main components include 10 olefins (orange), 9 alkanes (blue) and toluene (yellow). The data intuitively show that designed molecular sieves can effectively reduce most of these main components with emission reduction efficiency more than 30%. Except for 4-methyl-1-heptene, its average emission reduction efficiency is among higher than 50%. For alkanes, the emission reduction efficiency is slightly lower than that of olefins. The emission reduction efficiency shows the trend of n-alkanes > branched alkanes > cycloalkanes, effected by molecular structure.

3.2 Emission reduction efficiency of micro-mesoporous M/ZSM-5 molecular sieves

The comparison diagram of VOCs volatile factors and reduction efficiency was obtained as shown in Figure 6. The volatile factors range from 1.3-2.0 μg/g, all of which are lower than matrix asphalt. Compared with Figure 5, the total volatile factors significantly decrease mainly due to the sharp decline of benzene series. The emission reduction efficiencies of four metal-loading ZSM-5 shows that there is no increase of benzene series after metal-loading. Benzene series VOCs is no longer the key factor affecting emission reduction efficiency.

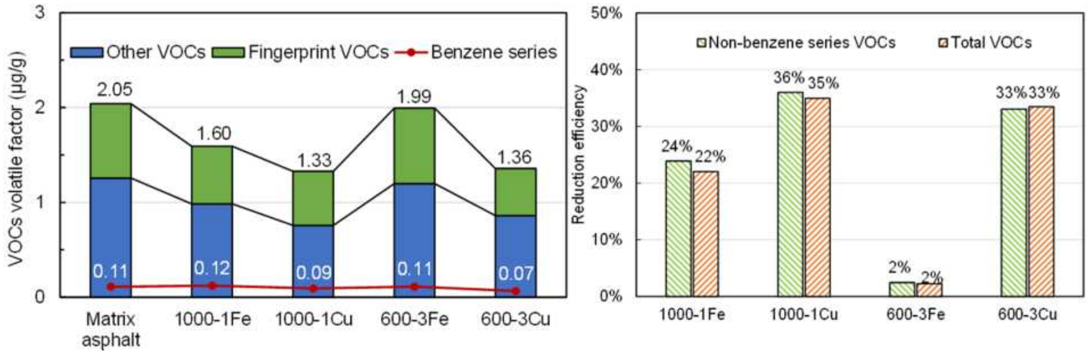

Figure 6: VOCs volatile factors and reduction efficiency of M/ZSM-5 modified asphalt

Figure 5 shows that the "Total VOCs" emission reduction efficiency of 600-3 and 1000-1 is 13% and -5%, respectively. After metal-loading, the emission reduction efficiency of 1000-1 is greatly improved, which is 22% (Fe) and 35% (Cu). The aromatic reaction is inhibited to achieve the reduction of benzene series VOCs. However, the emission reduction effect on "Non-benzene series VOCs" of 1000-1Cu and 1000-1Fe are 36% and 24%, which is lower than 1000-1 (37%). It indicates that although metal-load can reduce benzene series VOCs, the emission reduction effect of non-benzene series VOCs is hindered to the change of load site and acid strength.

In the catalysis field, the aromatization mechanism is very complex with four main steps, as shown in Figure 7. Firstly, there is the pyrolysis reaction of long-chain alkanes. Long-chain alkanes accept acid centre on the molecular sieve surface to become carbocation ions with high chemical activity. Through dehydrogenation, they are broken down into small molecule alkanes and olefins, including ethylene and propylene. Secondly, some small olefin molecules can be polymerized to produce C6-C8 olefins which are the main VOCs component. Thirdly, the olefin molecules undergo isomerization or cyclization to form aromatics precursors with six-membered rings. Finally, the aromatic precursors are exothermically dehydrogenated by the L-acid active centre of molecular sieve to form benzene series.

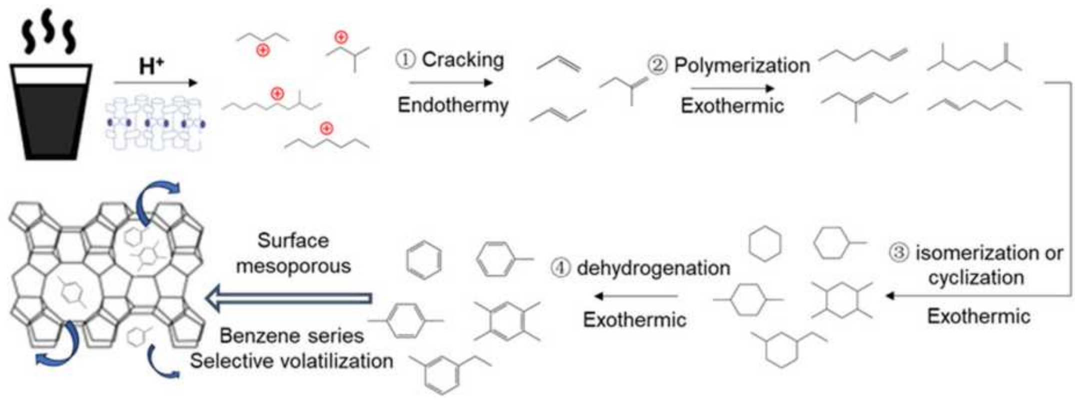

Figure 7 VOCs increasing mechanism of benzene series by adding micro-mesoporous molecular sieve

4 Conclusions

ZSM-5 molecular sieves were designed by the microstructure regulation and surface modification to achieve higher emission reduction efficiency. The following items can be concluded.

1. The designed micro-mesoporous ZSM-5 can effectively achieve "Non-benzene series VOCs" reduction ranging from 34% to 45%, especially alkanes and olefines.

2. Metal-loading can reduce the formation of benzene series by modifying and reconstructing the acid active centre and inhibiting the aromatization reaction. The emission reduction efficiency on "Total VOCs" is up to 35%. It reduces derivatives and organosulfur compound exceeds 60%.

Research on Data-Driven Decision-Making Technology for Green Pavement Maintenance and Quantitative Assessment of Carbon Emissions

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1 Objectives of this research

This study addresses the aging of highway infrastructure and the high-carbon nature of conventional maintenance. The aims are to: (1) build a multi-source data-driven decision-making framework to improve section segmentation granularity and maintenance-type matching; (2) develop a reusable data asset and defect recognition capability supported by a standardized full-scale GPR test road and a radar atlas database; (3) establish a quantitative evaluation system for energy use and carbon emissions (ECI, EAI, ECCI) to enable comparisons across processes and structural layers; and (4) quantify the economic, schedule, and environmental performance of green techniques represented by hot in-place recycling (HIPR), while clarifying applicability boundaries and implementation essentials.

2 Methodology and main research work

2.1 Methodology

1. **Multi-source sensing and test system:** A 450-m outdoor full-scale GPR test road was built with 129 embedded structural-defect types, resulting in a standardized radar atlas database and an automatic recognition system.
2. **Data platform and preprocessing:** A highly available storage scheme for multi-dimensional service data was established; drag-and-drop preprocessing (classification/regression/quantization/imputation) produced a dataset with ~200 influencing factors.
3. **Green technique mechanism and workflow:** For HIPR, a closed loop of heating (≈130–150 °C), milling, adding 3–5% rejuvenator, remixing, paving, and compaction was defined with key control points. Applicability covers functional surface distresses (e.g., transverse cracking, slight rutting ≤15 mm, flushing); structural capacity must satisfy PSSI ≥ 80 (FWD), with temperature/humidity constraints for construction.
4. **Carbon-evaluation framework:** Using the China Life Cycle Database (CLCD), a tiered calculation framework and indicators were formulated:

- **ECI (Energy Consumption Index):** energy per **mass** of technique;
- **EAI (Energy Assessment Index):** energy per **area** of project;
- **ECCI (Energy Consumption Cost Index):** CO_2 emissions monetized with emission factors and trading costs.

The four-process structure of maintenance was decomposed into calculable layers for comparative analysis across structural layers.

2.2 Main research work

Pain points were first identified (coarse sectioning, inaccurate maintenance type, and plan mismatch). A data foundation was then established via the test road, database, and preprocessing pipeline. Next, ECI/EAI/ECCI were computed for typical projects by structural layer to compare traditional and recycling-based techniques. In Projects B and D, in-place cold recycling (lower layer, B2) and plant hot recycling (upper layer, B1) were implemented. Finally, HIPR's mechanism, workflow, and parameter controls were evaluated for combined economic, schedule, and environmental benefits, and a V2.0 roadmap ("sensing—data—models—decision-making") was proposed.

3 Major findings

(1) **Process contribution:** Raw-material production and preheating before mixing dominate energy use (>81.6%); surface/overlay layers contribute >50% of total project-level emissions.

(2) **Technique comparison:** With recycling combinations in Project B, energy use fell by ~57.29% and carbon emissions by ~51.54% versus the baseline. At the technique level, HIPR reduced direct costs by ~20%, shortened construction time by ~30%, and cut total emissions by ~40% compared with conventional milling-overlay.

(3) **Applicability:** HIPR suits functional surface distresses and should not be directly applied to pronounced structural failures; PSSI ≥ 80 and suitable temperature/humidity conditions are required.

(4) **Outlook:** The pathway moves from a V1.0 regime dominated by 2D data and experience-based rules to V2.0 with integrated multi-modal sensing, 3D data governance, AI-based comprehensive evaluation, and a general modeling system, enabling multi-objective, intelligent, and green maintenance decisions with a curated library of efficient measures.

Parallel Session D4 Summary:

沥青老化严重降低沥青路面耐久性，是建设长寿命沥青路面亟需攻克的难题，但现有抗老化技术难以解决沥青路面在服役期间同时发生的热氧老化和紫外老化问题。武汉理工大学刘全涛教授提出沥青路面老化防治新思路：将抗氧剂插层组装到超分子紫外阻隔材料 LDH 层间，制备出兼有紫外光屏蔽和自由基捕捉能力的抗氧剂插层 LDHs（OLDHs），利用其从阻隔光、热、氧向沥青渗透和阻断沥青自由基链式老化反应两个层面，协同提升了沥青的抗热氧老化和抗紫外老化性能，并揭示了其对沥青老化路径和老化产物的影响规律，阐明了其协同提升沥青抗热氧老化和抗紫外老化性能的作用机理，为开发抗老化沥青、延缓沥青路面老化、提升沥青路面耐久性奠定了理论和应用基础。

胶粉沥青目前已得到广泛应用，但其存在污染问题，重庆交通大学唐乃膨副教授与长安大学耿九光副教授分别研究了橡胶改性沥青有害气体的减排，从而提升环境友好性和施工安全性。

重庆交通大学唐乃膨副教授汇报了高掺量橡胶沥青排放物量化与脱臭研究。高含量橡胶改性沥青（HCRMA）因其提升沥青路面耐久性以及高效回收固体废弃物的能力而被广泛应用。然而，HCRMA 可能带来的排放增加可能会引发空气污染问题，而这一问题尚未得到充分的定量评估和有效控制。因此采用气相色谱-质谱联用技术（GC-MS）对实验室采集的有机排放物进行了定量评估，并使用便携式气体分析仪对硫化氢（H_2S）、二氧化硫（SO_2）、氮氧化物（NO_x）和一氧化碳（CO）的实时排放浓度进行了监测。在实验中，分别向 HCRMA 中添加了蒙脱石、坡缕石和伊利石作为减排剂。在无机气体排放的除臭效果方面，蒙脱石同样优于伊利石和坡缕石。蒙脱石优异的减排与除臭效果归因于其较大的孔隙体积和良好的微观结构，流变性能影响也在可接受范围内，因此推荐了将蒙脱石作为 HCRMA 的减排剂使用。

长安大学耿九光副教授汇报了反应型净味剂对橡胶改性沥青硫化气体抑制机理研究。在道路施工过程中，使用胶粉改性沥青（CR MA）会释放出含硫异味气体，对环境和施工人员健康构成严重威胁。因此，必须采取有效措施控制 CR MA 中的硫化气体排放。橡胶硫化活化剂不仅能提高硫化反应的活性，还能增强硫化橡胶的交联密度和耐热性。基于 CR MA 中硫化气体生成机制、胶粉脱硫和降解的协同过程，采用气体分析仪研究了橡胶硫化活性剂——锌硬脂酸盐对硫化气体（H_2S、CH_4S、COS 和 CS_2）释放的抑制作用。锌硬脂酸盐通过抑制胶粉在沥青中的脱硫和降解过程，从而降低了硫化气体的产生。此外，锌硬脂酸盐与 H_2S 和 CH_4S 反应生成硫化锌（ZnS），进一步强化了其抑制作用。

中公高科养护科技股份有限公司仪明伟汇报了数据驱动的绿色路面养护决策技术与碳排放量化评估研究。阐明了养护转型的需求，依托多维数据基础以及人工智能技术，根据模型分析出养护规划项目库。报告从五个方面构建未来发展路径：检测监测、数字底座、诊断分析、智能决策以及绿色高效养护。

检测监测方面，目前以定期检测为主，未来将发展为以日常巡查、定期检测、多种手段融合的常态化智能感知体系，实现多维感知数据采集。

数字底座方面，现阶段以工程统计与二维图像数据为主，未来将实现数据三维升级，建立公路基础数据统一标准，融合多源数据，提升数据流通与数字平台的集成能力。

诊断分析方面，从当前依赖人工评价逐步迈向人工智能与专家系统结合的智能诊断体系，实现病害类型及成因的精细化识别。

智能决策方面，将由依赖专家经验转向基于模型的智能体系，通过构建通用化模型库与问答体，实现养护策略目标优化、精准绿色决策。

绿色高效养护方面，从经验性常规措施出发，构建高效环保养护体系，推荐绿色养护材料及工艺，实现节能减排。

报告强调了公路养护数字化转型、智能化提升与绿色可持续发展之间的协同推进。通过构建统一的数据底座和智能分析决策机制，有望实现公路养护由“被动响应”向“主动预防”转变，推动技术从传统走向现代化。未来工作的重点将集中在感知-分析-决策-养护的闭环系统构建与实践推广。

长安大学常郗文讲师围绕道路沥青材料挥发和高效减排现状开展了新材料开发研究，基于沥青 VOCs 的挥发特性，以微孔 ZSM-5 分子筛为基础，通过碱处理的微结构调控和金属浸渍法的孔道修饰，设计并制备了具有高效沥青 VOCs 减排的新材料。减排效率数据证实多孔分子筛材料的孔道结构确实提升了孔容和孔径分布，但一定程度上也导致高温下芳构化副反应加剧，从而导致排放的苯系物 VOCs 排放增多；对此，为实现对苯系物 VOCs 的高效减排，提出在分子筛内部进行金属负载的结构修饰，金属改善分子筛表面 B 酸和孔道内 L 酸分布与数量，有效提升了对苯系物 VOCs 的减排情况，最终实现了沥青 VOCs 超 35%的整体减排效果。

会议彰显了交通运输业向“智能化、绿色化、融合化”加速转型的趋势，基于近年来的研究成果，提出了路面绿色化发展的新材料新方向，共建了低排放道路建设与施工的可持续发展策略。未来应将持续深化减排材料升级及技术工艺革新，推动科技成果向实际工程应用转化，为构建绿色、高效、可持续的路面建设体系贡献核心驱动力。

Parallel Session E3

Topic: Sustainable Cement Materials for Transportation Infrastructure

Chair: Qiao Dong, Professor, Southeast University
Cochair: Hao Wu, Professor, Central South University

Introduction:

Cementitious materials serve as the backbone of modern transportation infrastructure, ensuring the durability, strength, and longevity of pavements, bridges, and other critical structures. These materials are not only enhancing the performance of traditional structures but also addressing emerging challenges related to environmental sustainability and long-term maintenance. These next-generation solutions not only surpass conventional performance benchmarks but also tackle pressing challenges in eco-efficiency, smart maintenance, and climate resilience. Emerging research focuses on high-performance cementitious composites, multi-scale modeling, and intelligent monitoring systems. The six featured presentations collectively address the pressing challenges of eco-efficiency, climate resilience, and lifecycle sustainability in infrastructure materials. Key highlights include:

(1) Next-generation high-performance cementitious composites refer to advanced cement-based materials with enhanced mechanical properties, durability, and adaptability to extreme conditions, developed through innovative ingredient combinations and structural designs.

(2) Multi-scale characterization and numerical simulation involve analyzing cement materials' properties and behaviors from micro to macro levels using experimental techniques and computer models to predict their performance.

(3) Low-carbon geopolymer stabilization technologies are eco-friendly methods that use geopolymer materials, with lower carbon emissions, to stabilize soils and other substrates, improving their engineering properties.

(4) Smart performance evaluation for cement materials utilizes advanced technologies like sensors and monitoring systems to assess the performance, durability, and health status of cement materials in real-time or through predictive analysis.

(5) Corrosion resistance measures for cement concrete are strategies and techniques aimed at preventing or reducing the corrosion of reinforcing materials within concrete, thereby extending the service life of concrete structures.

(6) Sustainability and environmental impact of cement materials focus on evaluating the entire lifecycle of cement materials, including raw material extraction, production, use, and disposal, to minimize their environmental footprint and promote sustainable development

Speech:

Fracture investigation and acoustic emission characteristics of semi-flexible pavement materials under different temperatures

Weimin Song, Yuanqi Liang, Xiaoyang Zhang, and Hao Wu, School of Civil

Engineering, Central South University

Study on the Synergistic Stabilization Effect of Solid Waste-Based Cement on Environmental Pollutants

Yongjie Ding, College of Metropolitan Transportation, Beijing University of Technology,

Experimental Study on a Novel Modified Magnesium Phosphate Cement Mortar Used for Rapid Repair of Portland Cement Concrete Pavement in Seasonally Frozen Areas

Changjun Zhou, Associate Professor, Dalian University of Technology

Properties of phosphogypsum-modified slope substrates

Shanshan Jin, Associate Professor, Beijing University of Civil Engineering and Architecture

Fluidized Solidification of Red Clay using Multiphase Phosphogypsum-Based Cementitious Material

Hao Wu, Haidong Huang , Weimin Song , De Zhang, Zhiqiang Cheng, School of Civil Engineering, Central South University

Nondestructive Evaluation of Concrete Permeability and Enhanced Corrosion Resistance via Surface Treatment

Qiao Dong, Professor, Southeast University

Fracture investigation and acoustic emission characteristics of semi-flexible pavement materials under different temperatures

Weimin Song [1], Yuanqi Liang [1], Xiaoyang Zhang [1], and Hao Wu [1]

[1] School of Civil Engineering, Central South University, 22 South Shaoshan Rd., Changsha, Hunan 410075, PR China

Graphical abstract

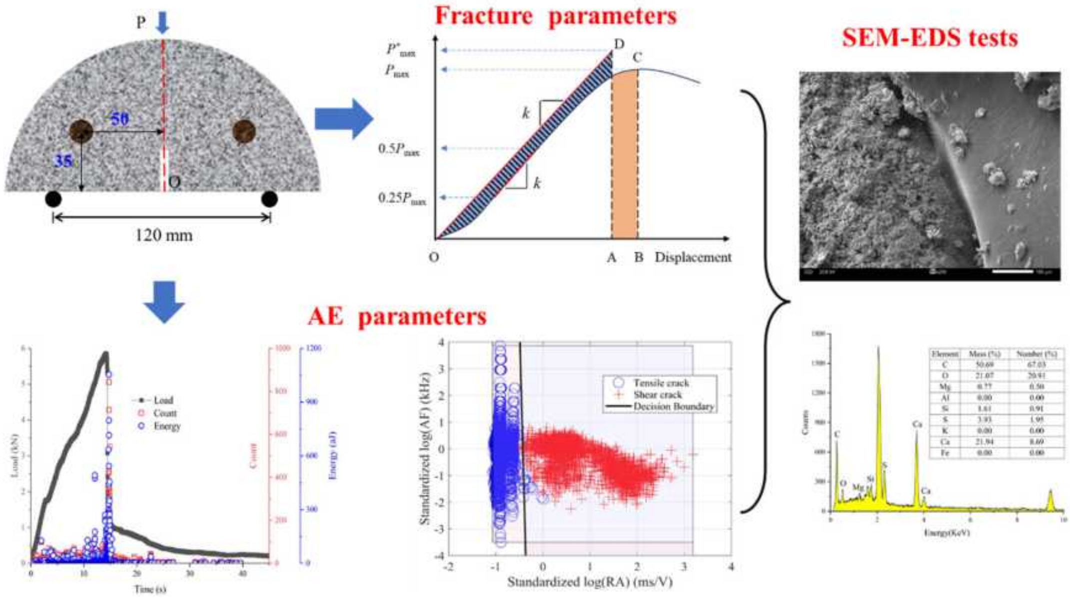


Figure 1 Graphical abstract

Abstract: Semi-flexible pavement (SFP) exhibits superior rutting resistance, yet its cracking performance remains a critical concern due to inadequate interfacial bonding between the porous asphalt mixture (PAM) and the grouting material. To address this challenge, this study investigated fracture behavior and interfacial enhancement strategies for SFP through silane coupling agent (KH550) modification. Fracture performance was assessed via semi-circular bending (SCB) tests at -10℃ and 25 ℃ , combined with acoustic emission (AE) monitoring and microstructural characterization. Results revealed that KH550 modification increased stress intensity factors by 10.7% and 8.9% at low (-10℃) and intermediate (25℃) temperatures, respectively, while enhancing total fracture energy by 55.1% and 29.3% under corresponding conditions. AE analysis highlighted distinct failure mechanisms: low-temperature (-10℃) fractures exhibited brittle failure with concentrated high-energy AE events, whereas the elevated temperature (25℃) promoted plastic deformation, suppressing AE activity. Gaussian Mixture Model (GMM) clustering and GMM + Support Vector Machine (SVM) clustering of rise angle (RA) and amplitude frequency (AF) data identified tensile cracking as the predominant failure mode, with KH550 further amplifying tensile crack ratios at -10℃ due to interfacial adhesion-induced brittleness. Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy

(SEM-EDS) confirmed KH550's interfacial enhancement, demonstrating denser hydration products and elemental redistribution at the asphalt-grout interface. These microstructural improvements correlated with macro-scale performance gains, where an optimized interfacial transition zone facilitated efficient stress transfer and crack resistance.

Study on the Synergistic Stabilization Effect of Solid Waste-Based Cement on Environmental Pollutants

Yongjie Ding [1]

[1] College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China, dingyongjie@bjut.edu.cn

Graphical abstract

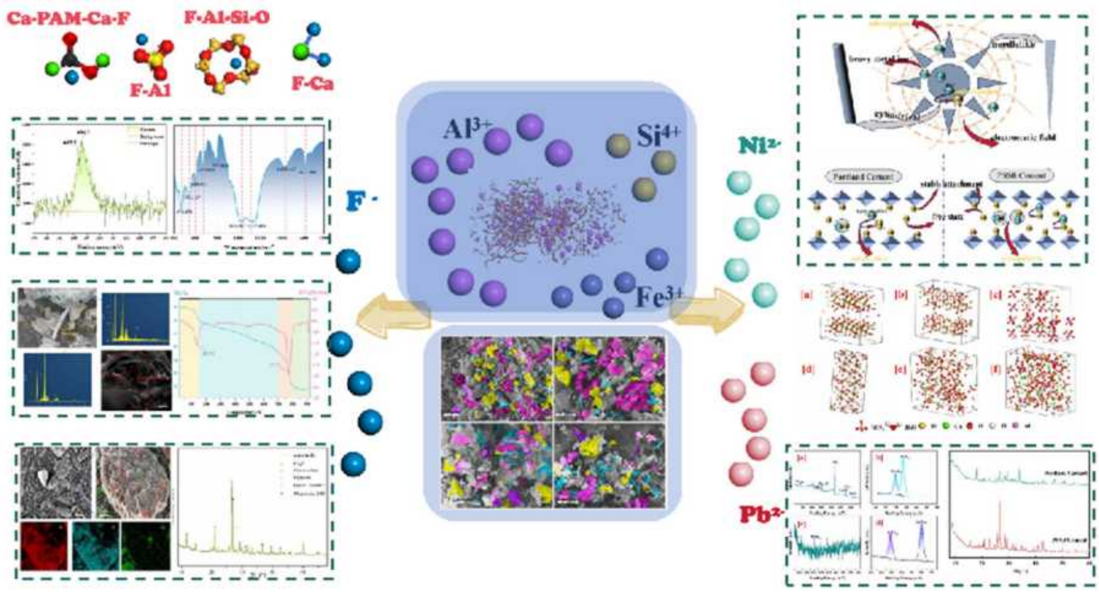


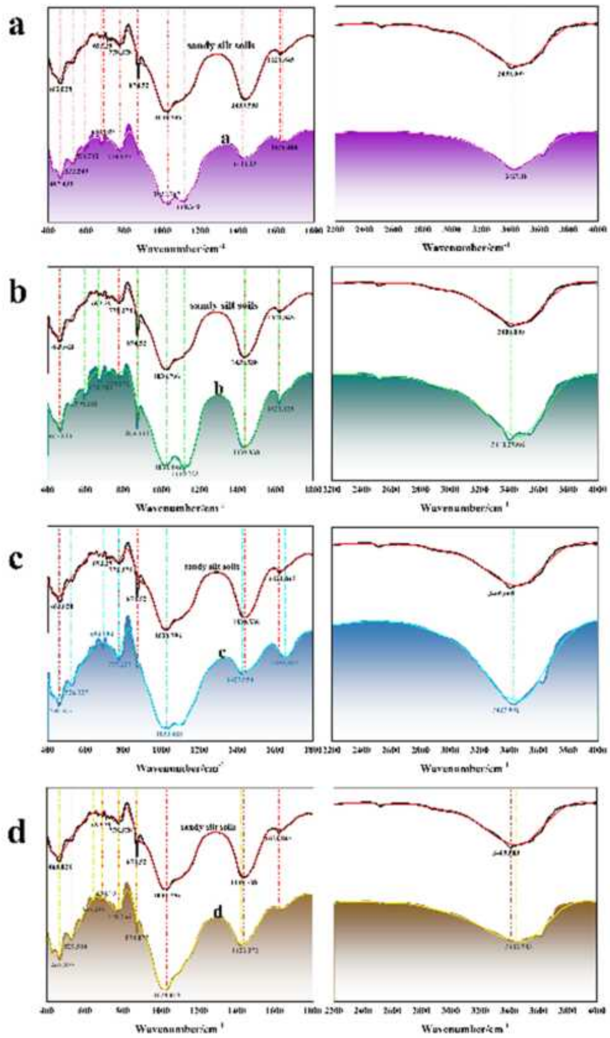
Figure 1 Graphical abstract

1 Objectives and Methodology

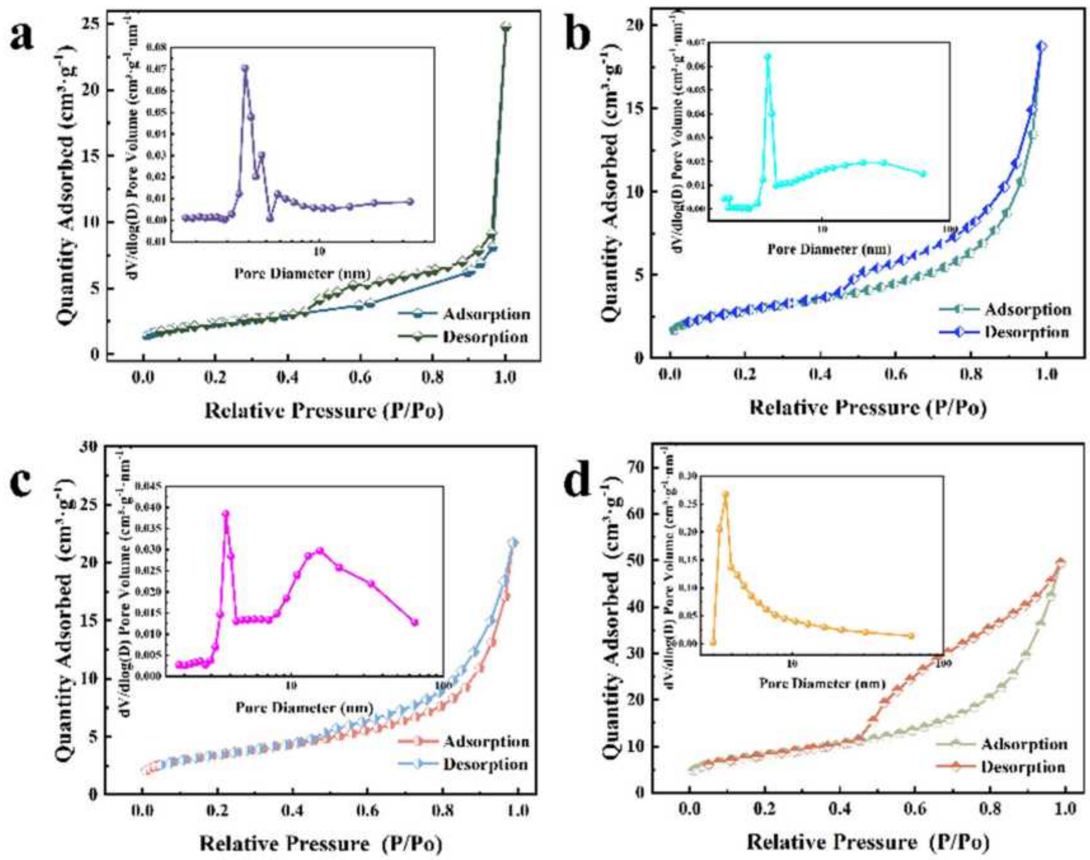
Despite numerous innovations in the low-carbon stabilization of soils with solid-waste-derived gels, the underlying design principles of such gels are still not fully elucidated. By formulating a range of modified gels, we determined that appropriate concentrations of Al^{3+} and Fe^{3+} lower the ζ-potential of soil particles, compress the electrical double layer, and thereby enhance flocculation. Alumina-rich systems foster uniform hydration and product formation, whereas silica-rich systems inhibit ettringite generation. Building on these findings, we compared the heavy-metal immobilization performance of oil-based drilling cuttings (OBDC) stabilized with ordinary Portland cement and with a phosphogypsum–steel-slag-based cement (PSSB). Relative to Portland cement, PSSB cut Ni and Pb leachabilities by 21.87 % and 47.32 %, respectively, evidencing superior immobilization capacity and structural integrity. The synergistic action of solid-waste-based gels and polymers was further explored by producing a firing-free ceramsite from PAM-modified phosphogypsum–slag geopolymer to stabilize fluorine-bearing sludge, achieving an F immobilization efficiency of 92.2 %. This high performance arises from the formation of F–Al–Si–O linkages, stable F–Al configurations, and strong adsorption of F^- via Ca–F and F–Ca^{2+}–COO^-–Ca^{2+}–F interactions.

2 Major results and findings

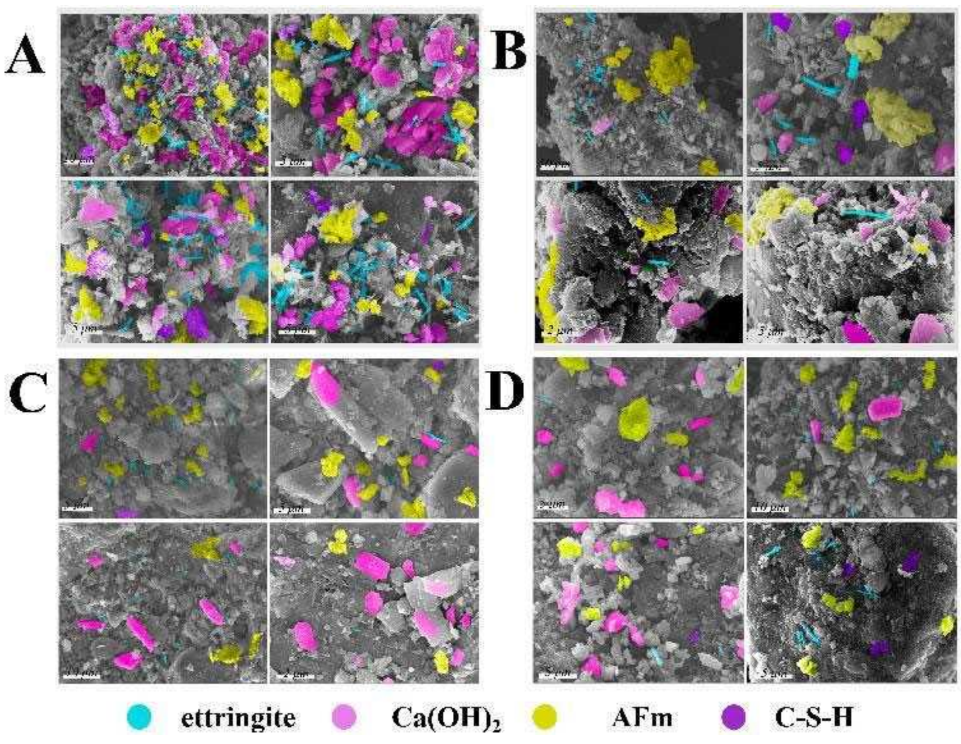
1. A high proportion of Al^{3+} enhances the binding capacity of adsorbed water, thereby increasing the availability of anionic adsorption sites within the electric double layer. Meanwhile, Fe^{3+} improves lattice symmetry and diversifies the coordination environment of adsorbed water through the stabilization of Fe-O bonds. In contrast, an excessive amount of Si^{4+} offers limited improvement to the overall solidification performance.



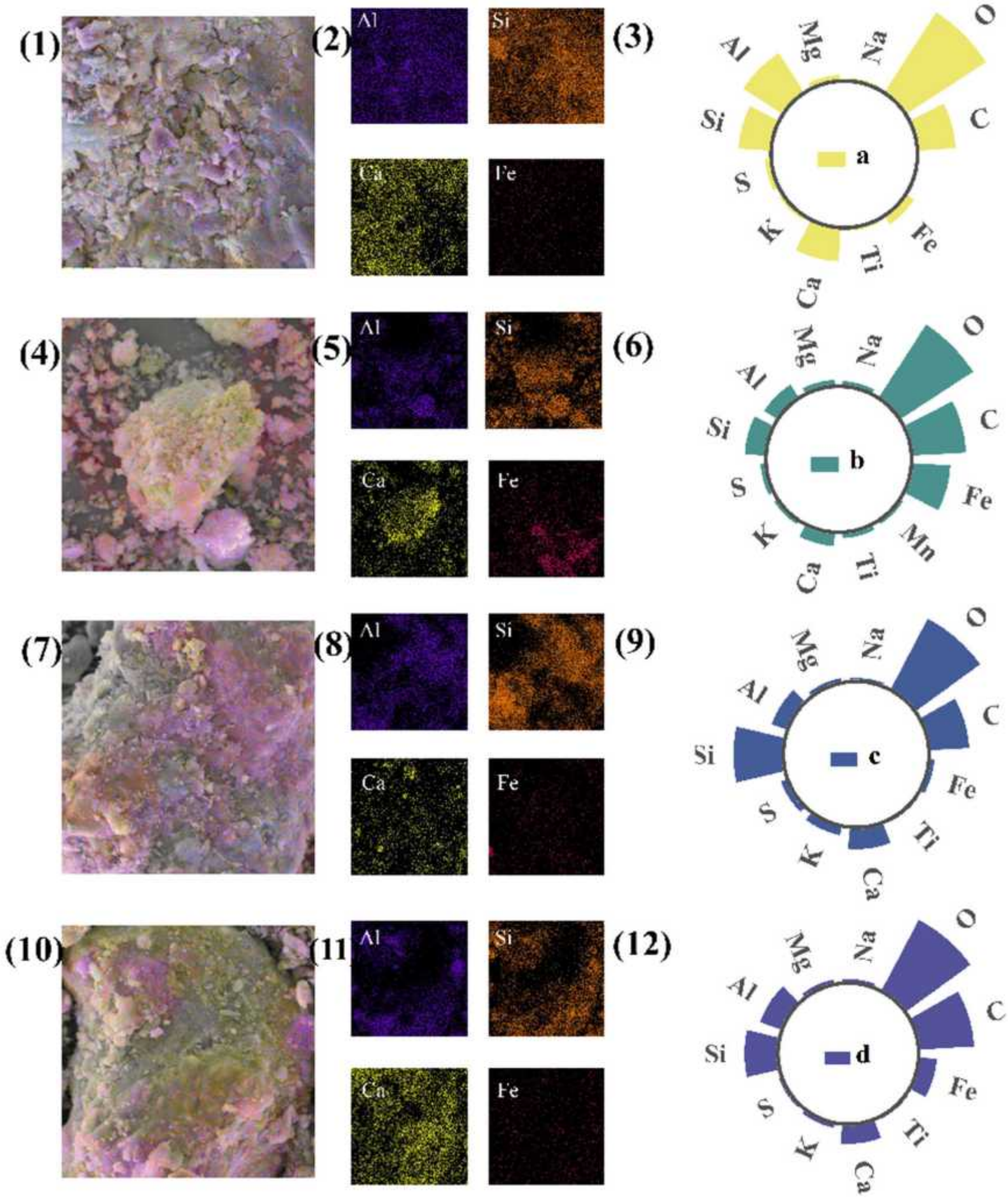
2. Soils stabilized with Al^{3+} exhibit the lowest porosity, highest compactness, and superior mechanical strength. In contrast, Fe^{3+}-modified systems show a slightly increased pore volume but maintain structural stability. However, Si^{4+}-modified stabilized soils tend to develop larger pores with higher pore connectivity, resulting in reduced overall strength.



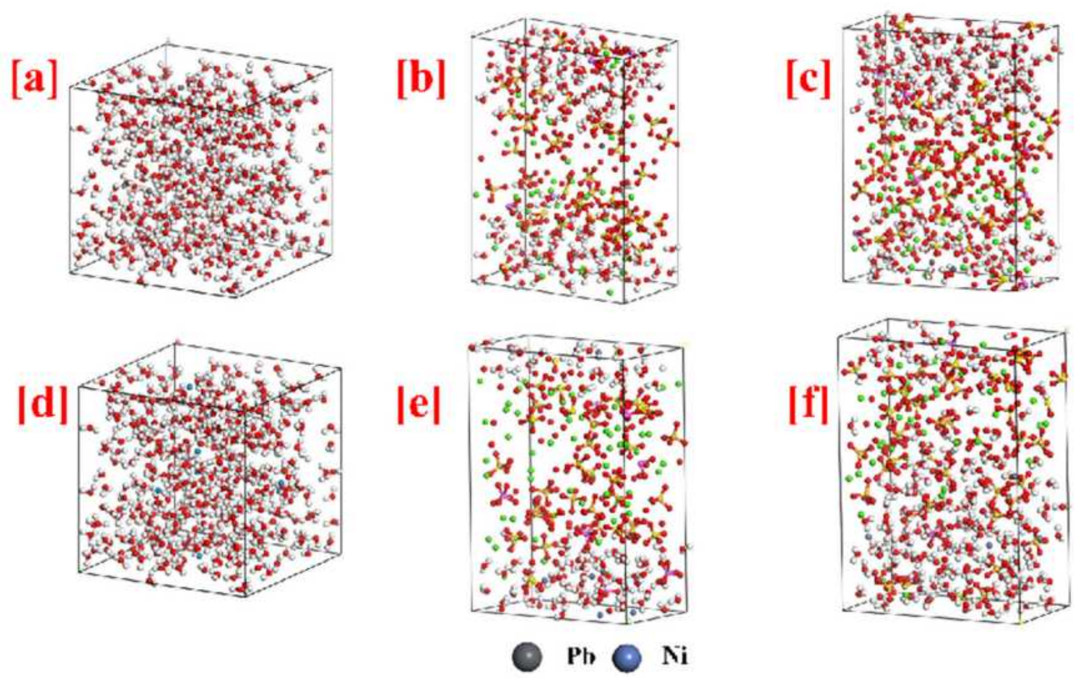
3. Al^{3+} promotes the uniform formation of ettringite (AFt), thereby enhancing the mechanical strength of the stabilized matrix. In contrast, a high concentration of Si^{4+} inhibits AFt formation, which subsequently reduces the yield of calcium-silicate-hydrate (C-S-H) gels and compromises strength development.



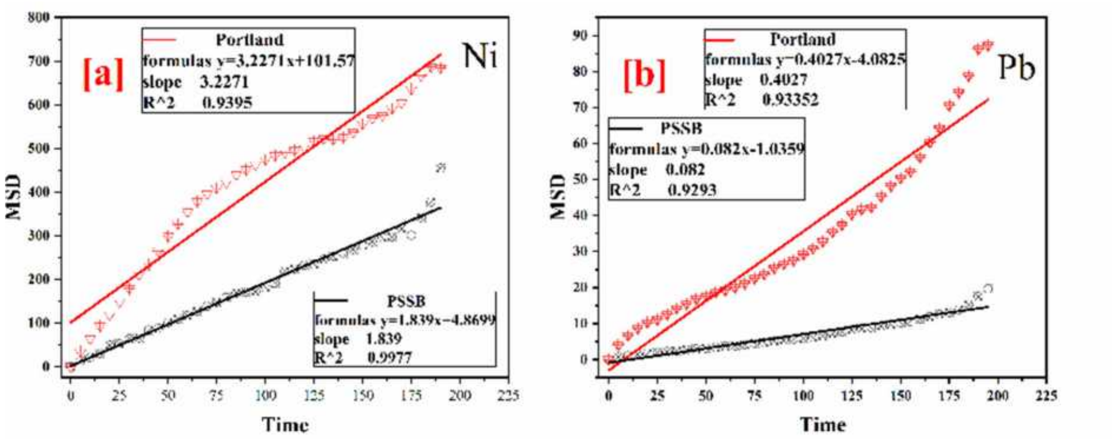
4. Uniformly distributed Al^{3+} facilitates the formation of silicate structures and promotes the generation of calcium-silicate-hydrate (C-S-H) gels. Fe^{3+} synergistically interacts with Al^{3+} and Si^{4+} to form a stable Fe-Al-silicate network, thereby enhancing the binding capacity of the matrix. In contrast, excessive Si^{4+} often suffers from limited diffusion, leading to incomplete reactions and reduced gel formation.



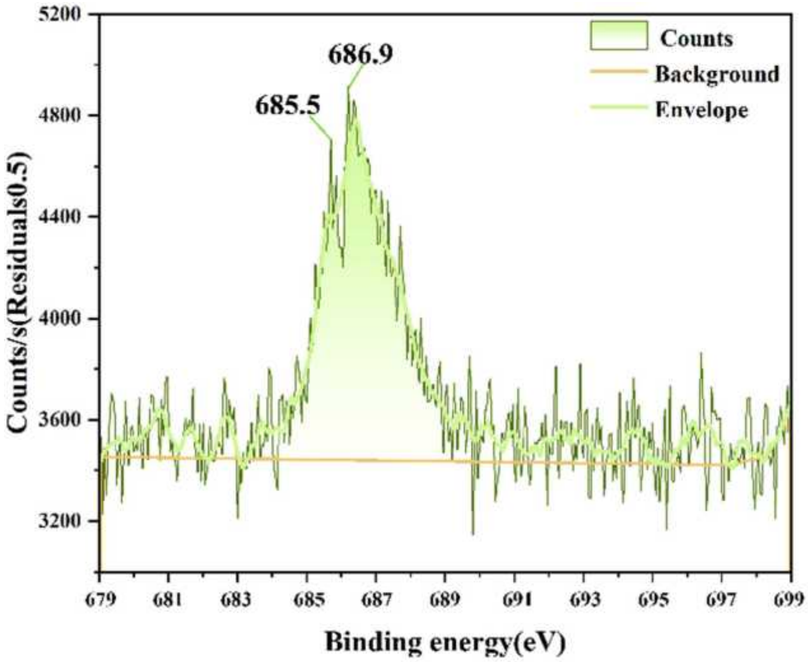
5. The diffusion modeling of heavy metal ion immobilization in solid-waste-based cementitious materials.



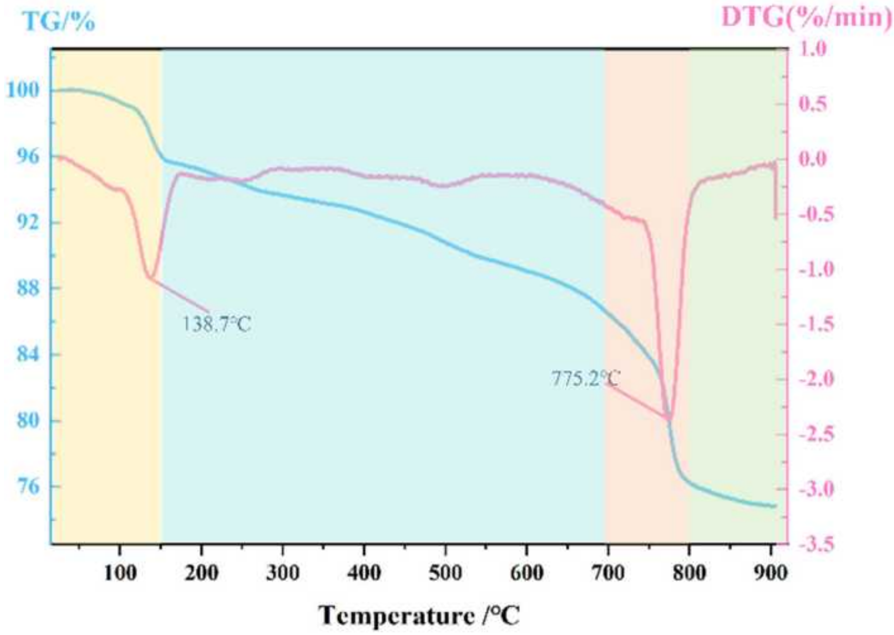
6. Mean square displacement (MSD) analysis revealed that the diffusion coefficients of Ni^{2+} and Pb^{2+} in PSSB cement decreased by 42.92% and 79.63%, respectively.



7. Fluorine exists in dual peak forms at 685.5 eV, corresponding to electrostatic adsorption in Ca-F and F-Al bonds, and at 686.9 eV, attributed to ligand exchange mechanisms involving F-Al-O bonding, along with a minor peak representing the free ionic state.

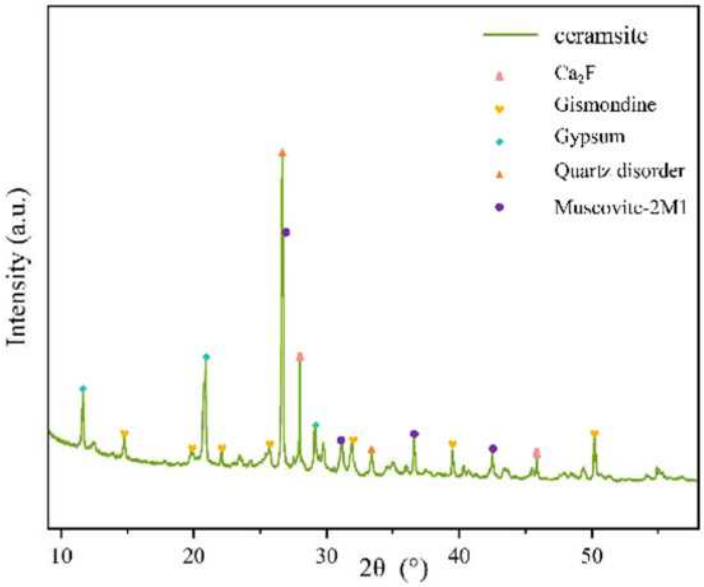


8. The organically modified geopolymer-based firing-free ceramsite undergoes a multi-stage decomposition process between 25 °C and 900 °C, including the removal of bound water and volatilization of PAM residues (25-150 °C), the release of low-boiling-point substances (with a 7.16% weight loss at 138.7 °C), and polymer chain scission (resulting in a cumulative 18.01% weight loss at 775.2 °C). After thermal treatment at 900 °C, a residue of 74.82% remains, predominantly composed of thermally stable aluminosilicate phases such as Gismondine and Muscovite, which contribute to the effective immobilization of fluorine pollutants.

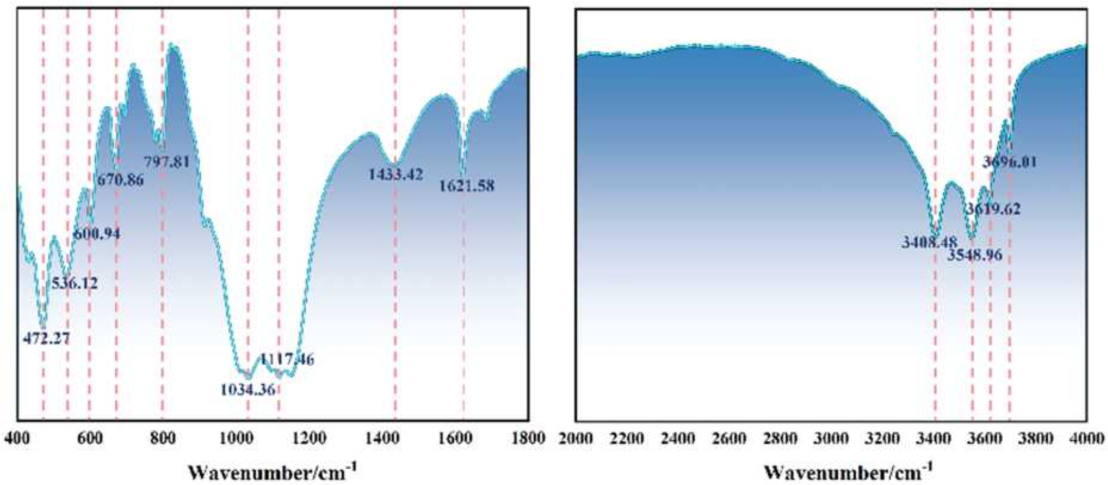


9. Muscovite anchors F^- ions through an "interlayer electrostatic entrapment" mechanism, while the three-dimensional microporous framework of anorthite, in conjunction with the formation of calcium fluoride (CaF_2), contributes synergistically

to the immobilization of fluoride ions.



10. The carboxylate vibrations at 1621-1433 cm⁻¹ indicate the hydrolysis of PAM to form carboxyl groups, which reinforce the gel interface via Ca^{2+}-COO^--Ca^{2+} ionic bridging. The Ca-F bond vibrations at 797-670 cm^{-1} and the Si-O-Si bending vibration at 472 cm^{-1} confirm that fluoride ions enter the calcium-based phases through ion exchange and are physically encapsulated within the aluminosilicate network.



Experimental Study on a Novel Modified Magnesium Phosphate Cement Mortar Used for Rapid Repair of Portland Cement Concrete Pavement in Seasonally Frozen Areas

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1 Objectives of this research

Due to its good mechanical properties and rapid condensation, MPC mortar seems an appropriate rapid repair material for PCCP. However, the impacts of a freeze-thaw environment and vehicle loading in seasonally frozen areas on MPC mortar have been rarely studied, which are the issues this study would address. The objectives are to study a novel basalt fibre-reinforced and styrene-butadiene copolymer-modified magnesium phosphate cement (BFPMPC) mortar and the properties of the BFPMPC mortar as a rapid repair material for PCCP with environmental influences.

2 Methodology and main research work

2.1 Methodology

Introduce your methodology with a roadmap.

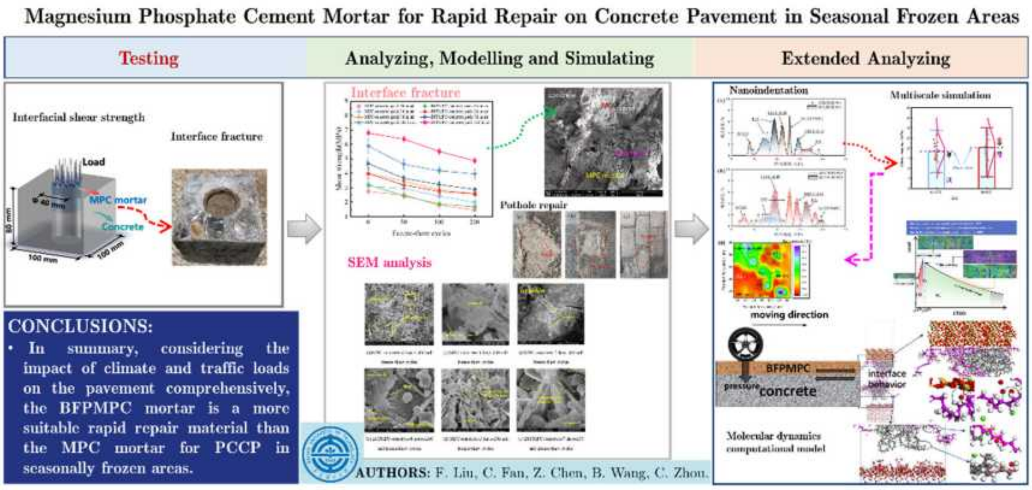
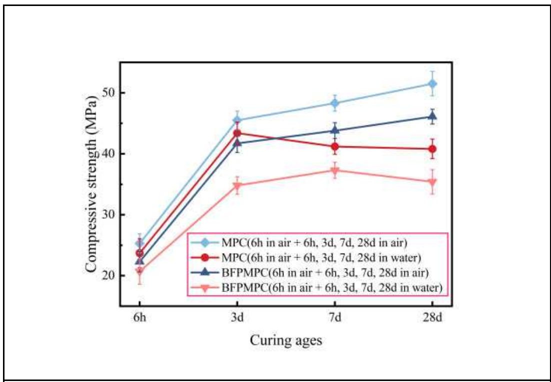
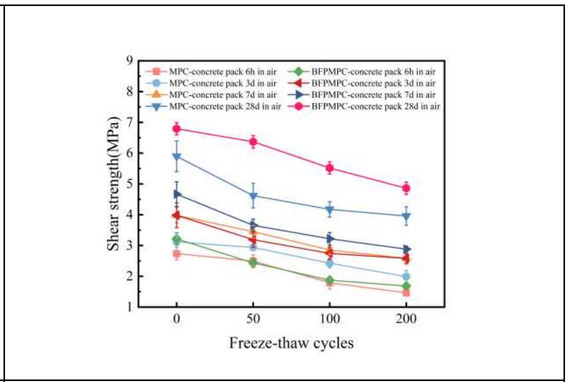
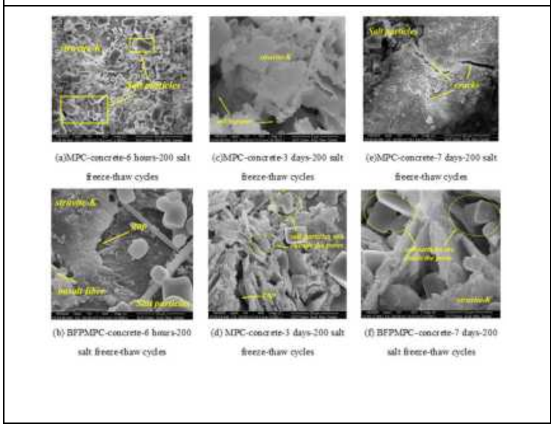
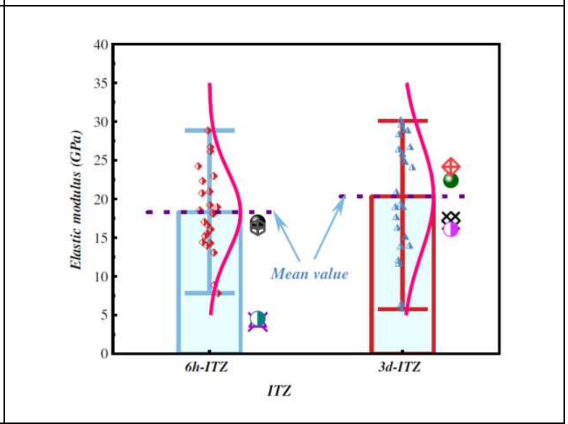
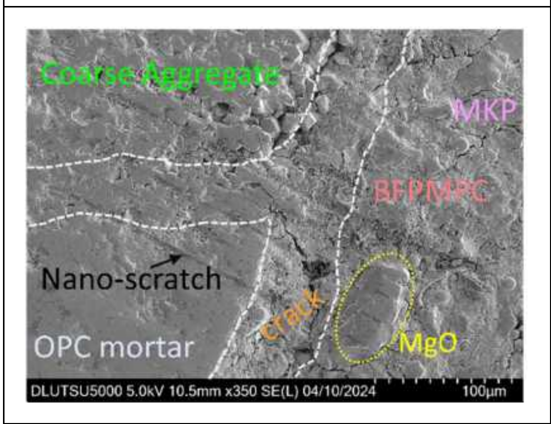
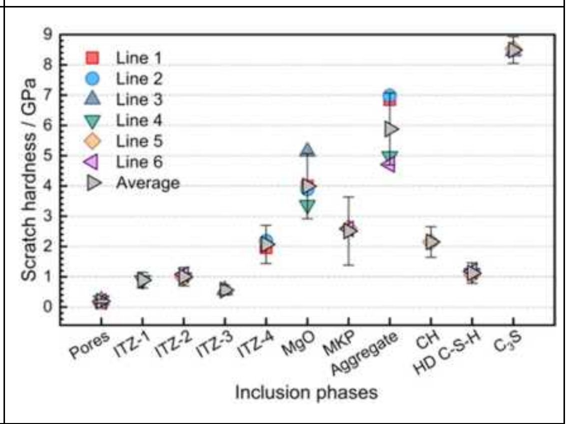
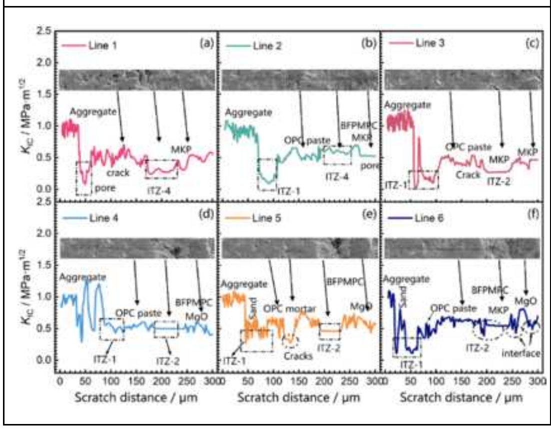
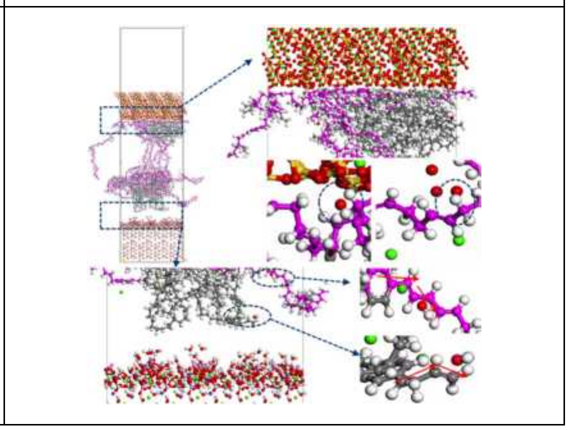


Figure 1 Research roadmap

2.2 Main research work

Introduce the main research work and results with tables and figures.

Table 1 Main research work

3 Major findings

The experimental results showed that the BFPMPC mortar proposed has not only reliable compressive and flexural strengths but also good water resistance in the ITZ and good bonding performance with the old cement concrete. Although the strength retention rate of the BFPMPC mortar is lower than that of the MPC mortar, the BFPMPC mortar still has good freeze-thaw resistance. Compared to MPC mortars, the flexural strengths of the BFPMPC mortars are enhanced. Under the water cured, the flexural strength of both the MPC and BFPMPC mortars initially increase until 3 days curing age and then decline with a similar growth trend strength. In both curing methods, the shear strength of the BFPMPC-concrete packs at each curing age is larger than the MPC-concrete packs. It is also found that water-cured packs exhibit slightly lower shear strength than air-cured packs. As mentioned previously, unhydrated phosphate was dissolved out from MPC in the water-cured, which changed the pH environment of the aqueous solution and led to the hydrolysis of hydration products $MgKPO4·6H2O$ in an acidic environment, increasing the porosity of the system. However, no significant difference exists between the shear strength of air-cured packs and water-cured packs. such network and bridging effects also improve the fracture toughness of BFPMPC-concrete ITZ, resulting in a much higher allowable displacement in the shear test of the BFPMPC-concrete pack than the one in the MPC-PCP ITZ. Also, obviously, the fracture energy of the former is much higher than the latter. With the addition of polymer molecules, BFPMPC makes a stronger bonding in the ITZ formed with cement concrete rapid repairing, which has a good bond ability originally. Additionally, the ITZ between the BFPMPC mortar and old concrete has good freeze-thaw resistance. Then, the salt freeze-thaw cycles were found more destructive to the repair interface than freeze-thaw cycles. A preliminary conclusion may be summarized that at the initial stage of freeze-thaw or salt freeze-thaw cycles, a small amount of water can penetrate deep along the voids in ITZ for a certain permeability, greatly decreasing the shear strength of ITZ after damage. Then, the possibility of water infiltration into ITZ may become more and more difficult with the increase of time in a longer period for the subsequent infiltration when a large amount of water is resisted, resulting in the slowdown failure trend in the damage data of 100–200 freeze-thaw cycles. Salt crystals are retained in the ITZ, which is the biggest potential for structural damage. Therefore, the salt freeze-thaw cycles make the shear strengths of repair material, and concrete packs decrease more than the freeze-thaw cycles due to the significance analysis. The preceding analysis further indicates that the damage of the salt freeze-thaw cycle has a greater influence on the bond strength of the repair materials in ITZ. The addition of the styrene-butadiene copolymer (SBC) emulsion in BFPMPC mortar was formed without new hydration components, which was observed by X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FT-IR). The ability to enhance the bonding strength with the addition of SBC was found by scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS). The SBC emulsion can be well fused with MPC and old concrete in the ITZ. Not only are the cracks of the BFPMPC-concrete ITZ fewer, but also the formation of the network structure played an important role in hindering the fracture process of BFPMPC-concrete ITZ. The SBC emulsion can also wrap fibres more thoroughly. And these microstructures improved the flexural strength and shear strength. When curing ages reached 7 days, salt crystal particles were embedded in the aperture of the hydration products to achieve the damaging effect. The salt crystal particles have been in the crack of the interface structure in the freezing period. Until the next freeze-thaw cycle begins, the dissolved salt crystal particles in the pore water as the increase of temperature has seeped into the ITZ. In summary, considering the impact of climate and traffic loads on the pavement comprehensively, the BFPMPC mortar is a more suitable rapid repair material than the MPC mortar for PCCP in seasonally frozen areas.

Properties of phosphogypsum-modified slope substrates

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[2] School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing, 100044, China, wzh101011@163.com
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Graphical abstract

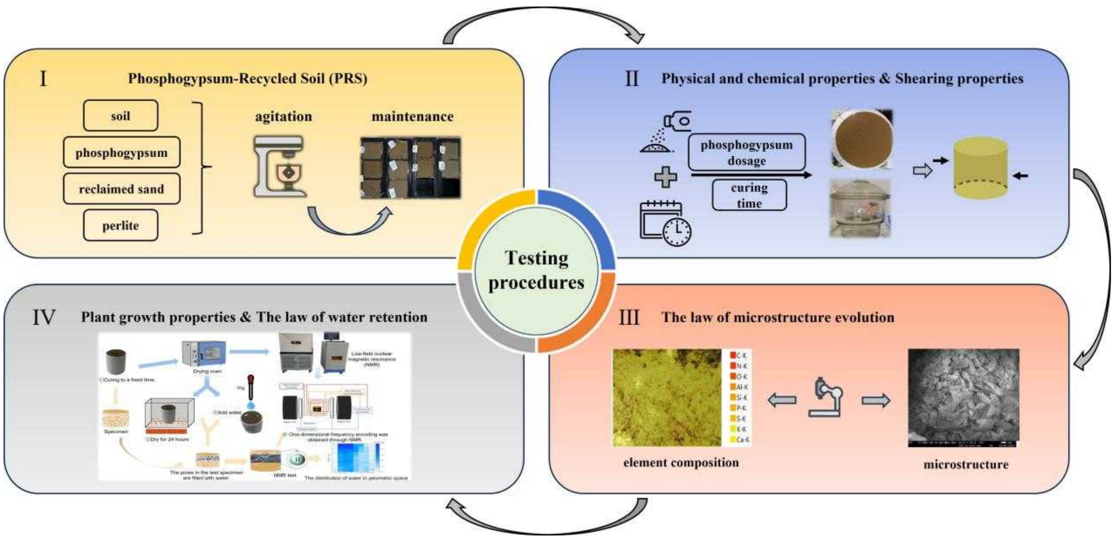


Figure 1 Graphical abstract

1 Objectives and Methodology

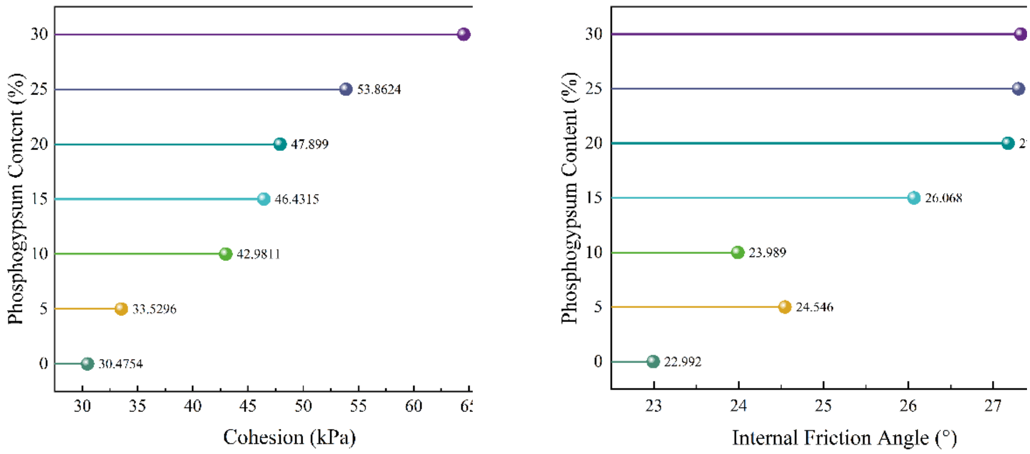
The purpose of this study is to explore the effects of different phosphogypsum dosage and curing time on the mechanical properties and shear properties of PRS (Phosphogypsum-Recycled Soil) substrate through laboratory tests, and to reveal its internal mechanism by combining SEM and MIP data for microstructure analysis. The research results will provide theoretical basis and technical support for the design and application of base materials in slope ecological restoration, and promote the utilization of solid waste resources and the sustainable development of ecological environment.

The direct shear test was conducted on the PRS substrate using the ZJ-type strain-controlled direct shear machine. The shear strength and internal friction angle of the PRS substrate were determined. The microstructure was examined by scanning electron microscopy (SEM), and EDS energy spectrum scanning and microscopic morphology observation were also carried out. The pore structure of the PRS substrate was analyzed by AutoPore V 9620 fully automatic mercury intrusion porosimetry, with the pore size range being 3 nm to 950,000 nm. The pore structure information, including pore volume, pore size distribution and porosity, was determined.

2 Major results and findings

As can be seen from Figure 2 (a), the cohesion showed a certain positive correlation with the phosphogypsum dosage amount. Specifically, when the phosphogypsum dosage is gradually increased from 0% to 30%, the corresponding values of cohesion of the slope substrate are 30.4754 kPa, 33.5296 kPa, 42.9811 kPa, 46.4315 kPa, 47.899 kPa, 53.8624 kPa, and 64.5282 kPa. Compared with the substrate without phosphogypsum, the cohesion of phosphogypsum increased by 10.022%, 41.035%, 52.357%, 57.173%, 76.741% and 111.739% for each 5% increase of phosphogypsum. Therefore, phosphogypsum is an effective substrate reinforcing material. Cohesion is the ability of soil particles to resist shear failure due to intermolecular attraction, chemical bonding and friction between particles. The addition of phosphogypsum enhances the cementation between soil particles and improves the overall strength of soil, so the cohesion of PRS substrate is further improved. The internal friction angle of the soil is an important index of the friction characteristics of the soil, which is mainly composed of the friction force on the surface of the soil particles and the bite force generated by the embedding and interlocking between the particles. As shown in Figure 2 (b), the overall trend of the internal friction angle increased with the increase of phosphogypsum doping. When the phosphogypsum dosage increased from 0% to 30%, the internal friction angle of the substrate increased by 6.76%, 4.34%, 13.38%, 18.2%, 18.73%, and 18.85%, respectively. Among them, the increase in the angle of internal friction was faster when the doping of phosphogypsum was in the range of 10% to 20%, it can be seen that the incorporation of phosphogypsum effectively enhances the cohesion between particles, makes the embedding between particles closer, reduces the possibility of dislocation, and then increases the internal friction angle. However, once the dosage of phosphogypsum exceeds 20%, the increase in the angle of internal friction becomes extremely limited. When the content of phosphogypsum is too high, the wrapping of soil particles has formed a stable structure, which slows down the growth of internal friction angle to a certain extent. As can be seen from Figure 3, the shear strength of PRS substrates with different phosphogypsum dosage show an overall increase with the growth of the maintenance age, but the growth trend under each dosage is slightly different. The test results indicate that phosphogypsum effectively fills the voids between soil particles, thereby enhancing the cementation between soil particles. Through the construction of GBDT-C model and GBDT-IFA model, it is concluded that the importance of phosphogypsum dosage on adhesion force and internal friction angle is 81.9% and 57% respectively, proving that the dosage of phosphogypsum has a very significant impact on the adhesion force of the substrate and a relatively large impact on the internal friction angle. With the increase in the dosage of phosphogypsum, the soil particles are gradually covered by rod-shaped $CaSO_4 \cdot 2H_2O$, transitioning from a loose state to a network-wound state, and finally forming a stronger whole with the soil particles, as shown in Figure 4. At the same time, $CaSO_4 \cdot 2H_2O$ splits the large pores in the matrix into capillary pores, optimizing the pore structure and improving the shear strength of the soil. With the increase in the dosage of phosphogypsum, the pore volume content curve of the PRS substrate gradually transitions from a bimodal type to a unimodal type; the maximum effective pore diameter and median pore diameter show a trend of first decreasing and then increasing, and the peak shows a trend of first increasing and then decreasing, and the pore structure undergoes a process of first strengthening and then weakening, as shown in Figure 5.

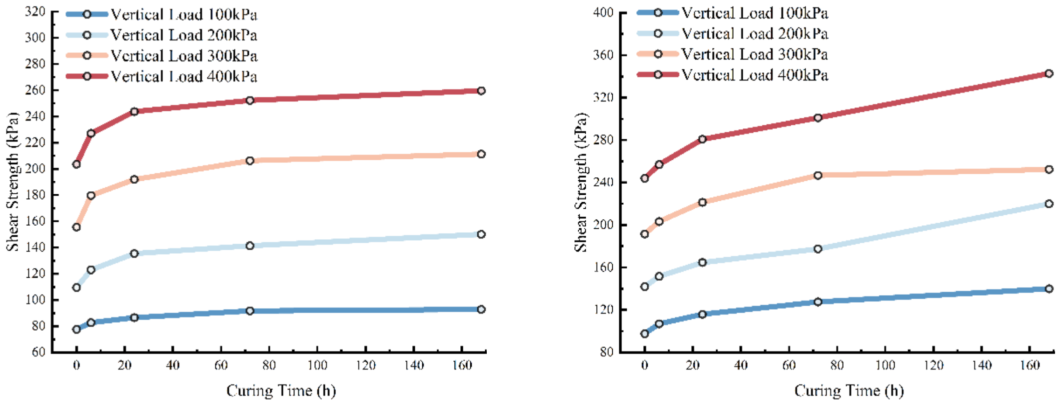
In order to improve the mechanical properties of the slope substrate, the cementitious effect of phosphogypsum was used to improve the substrate. The shear strength, related parameters and microstructure of the substrate were tested and the response analysis was made to explore the effects of different amounts of phosphogypsum and different curing ages on the substrate.



(a) The relationship between phosphogypsum dosage and cohesion

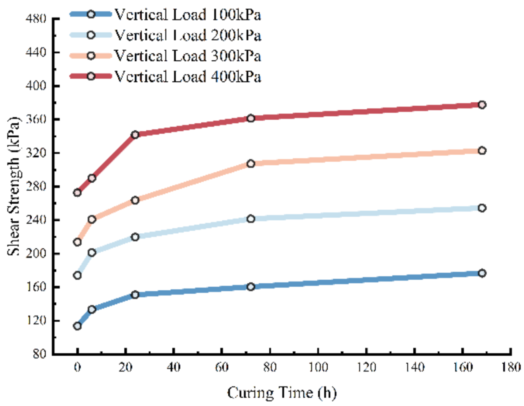
(b) The relationship between phosphogypsum dosage and internal friction angle

Figure 1. phosphogypsum dosage versus cohesion, angle of internal friction



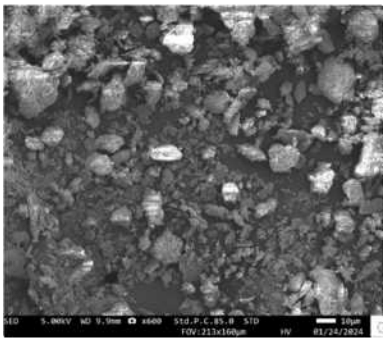
(a) phosphogypsum dosage 0%

(b) phosphogypsum dosage 15%

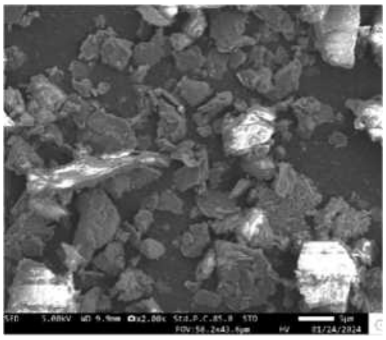


(c) phosphogypsum dosage 30%

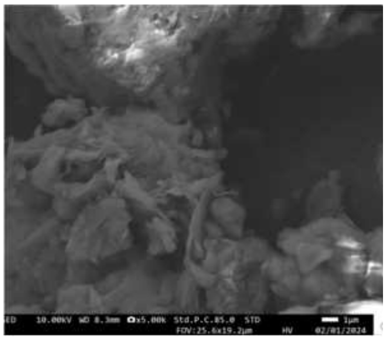
Figure 2. Variation of shear strength with curing age under different vertical loads



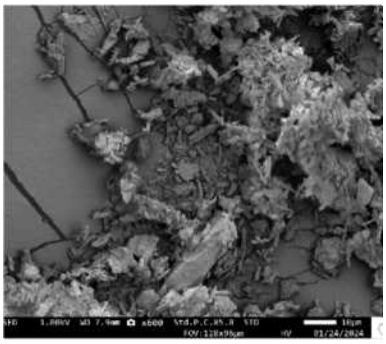
(a) phosphogypsum 0 % under 600 times



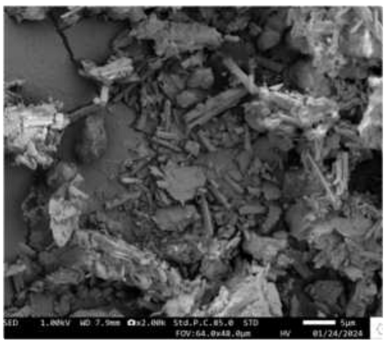
(b) phosphogypsum 0 % under 2000 times



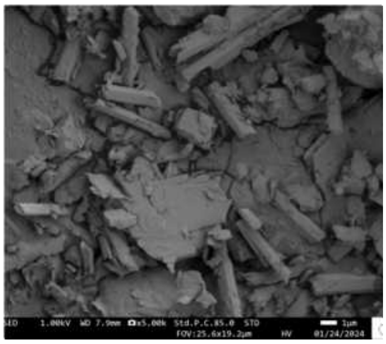
(c) phosphogypsum 0 % under 5000 times



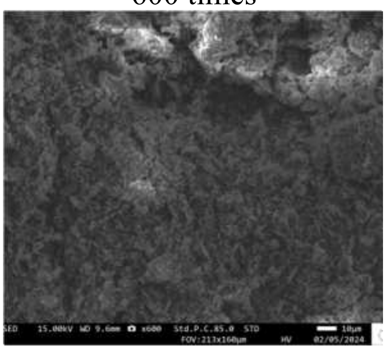
(d) phosphogypsum 15 % under 600 times

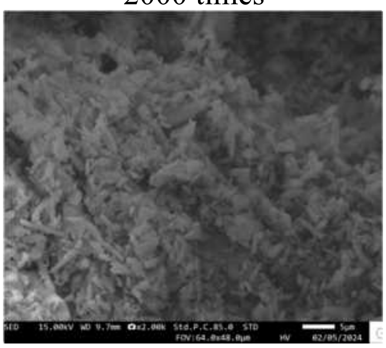


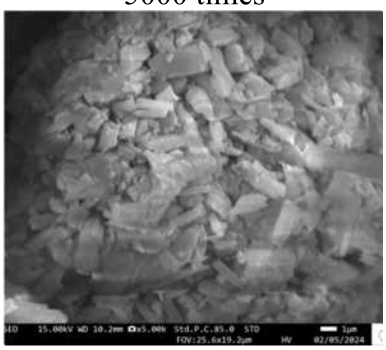
(e) phosphogypsum 15 % under 2000 times



(f) phosphogypsum 15 % under 5000 times







(g) phosphogypsum 30 % under 600 times

(h) phosphogypsum 30 % under 2000 times

(i) phosphogypsum 30 % under 5000 times

Figure 3. SEM results for different phosphogypsum dosages at different magnifications

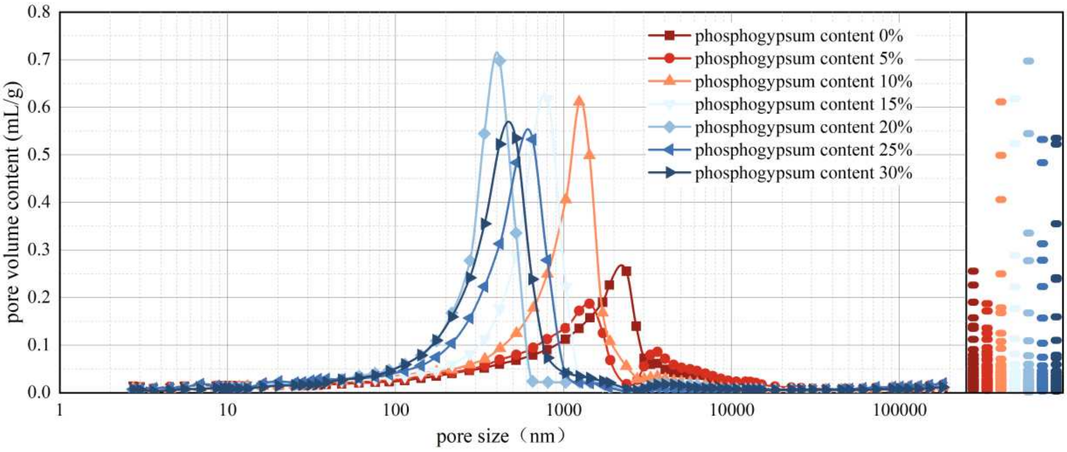


Figure 4. Pore size distribution curves for different phosphogypsum dosages

Fluidized Solidification of Red Clay using Multiphase Phosphogypsum-Based Cementitious Material

Hao Wu [1], Haidong Huang [1], Weimin Song [1,*], De Zhang [2], Zhiqiang Cheng [2]
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1 Objectives of this research

The primary objective of this study is to introduce a multiphase phosphogypsum-based cementitious material (PBCM), mainly composed of hemihydrate and anhydrous PG, with ordinary Portland cement and slag powder as supplementary cementitious materials. The development of PBCM was evaluated on a comprehensive analysis of the mineral composition of the constituent materials and the fundamental principles governing cementitious systems. Specially engineered to the fluidization and solidification of red clay, PBCM was designed to enhance both the mechanical properties and durability of the fluidized-solidified red clay (FSR). Furthermore, a detailed microstructural analysis was conducted to interpret the morphological evolution of FSR during various stages of curing and a comprehensive discussion was also presented to elucidate the solidification mechanism of the FSR.

2 Methodology and main research work

2.1 Methodology

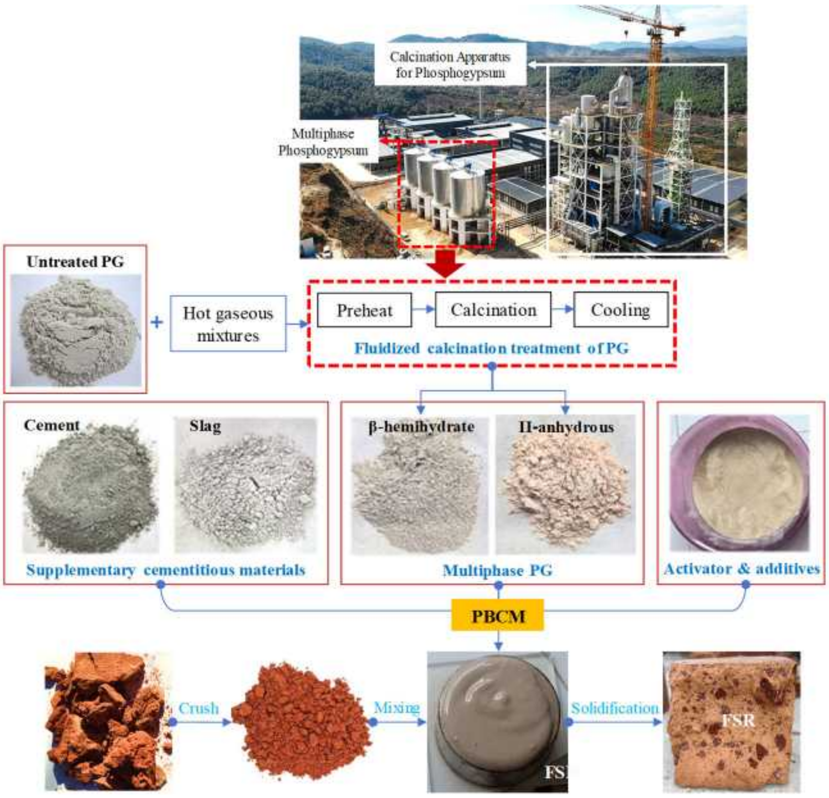
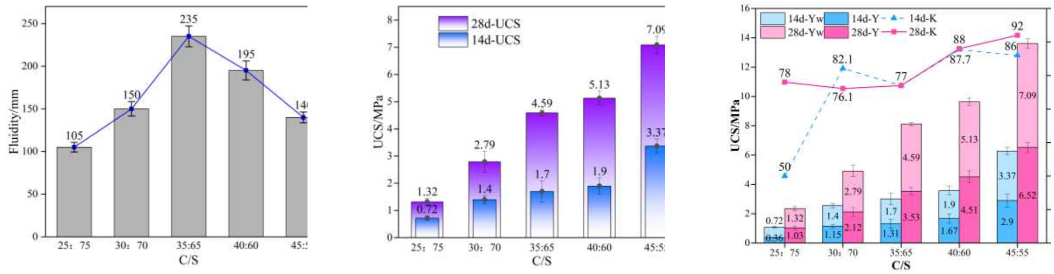


Figure 1 Research roadmap

2.2 Main research work



(a) Influence of C/S on flowability (b) Influence of C/S on strength (c) Influence of C/S on water stability

Figure 2 Influence of C/S ratio on performances of FSR

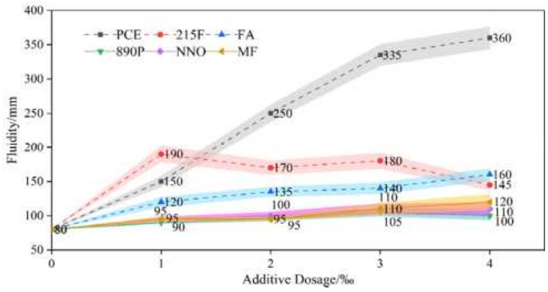


Figure 3 Influence of additive on flowability

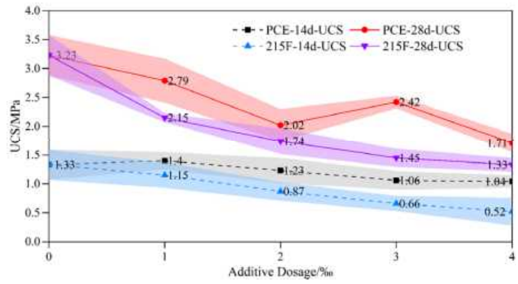
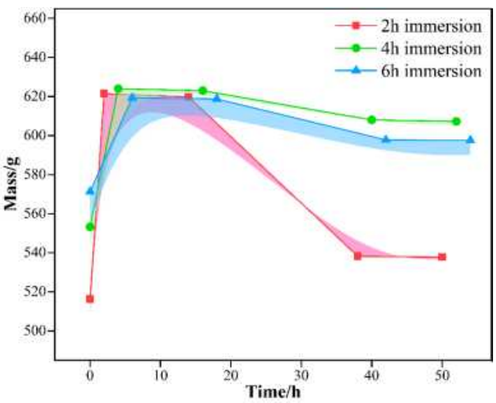
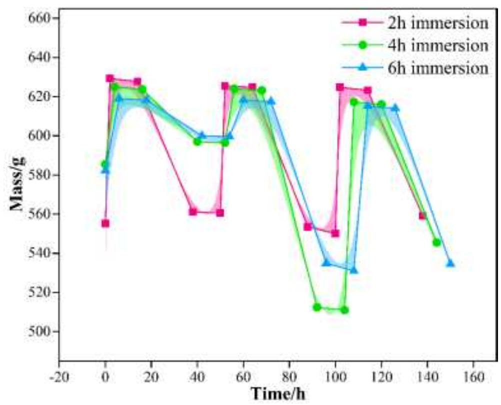


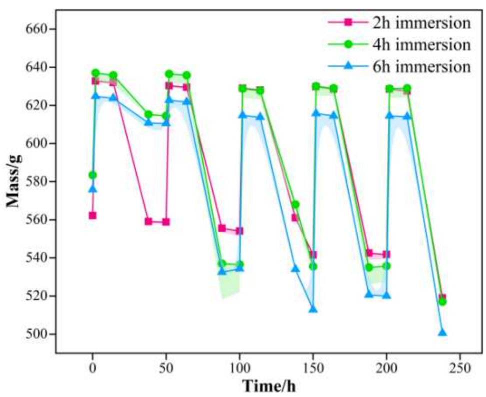
Figure 4 Influence of Additive on Strength



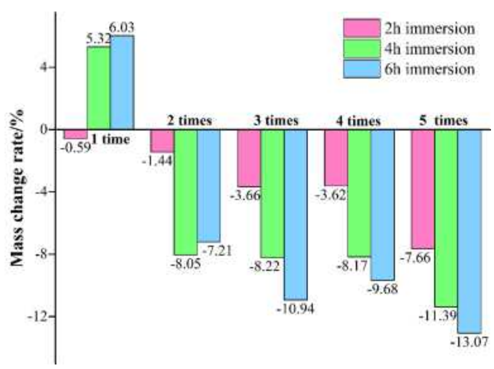
(a) One wet-dry cycle



(c) Three wet-dry cycles

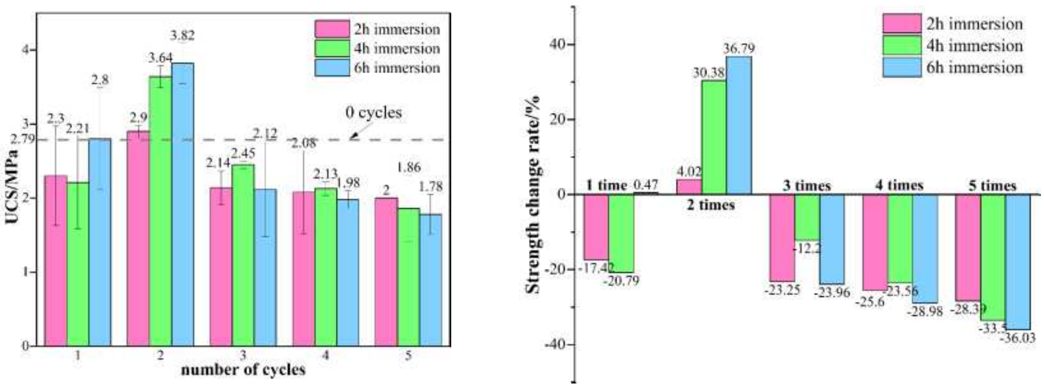


(e) Five wet-dry cycles



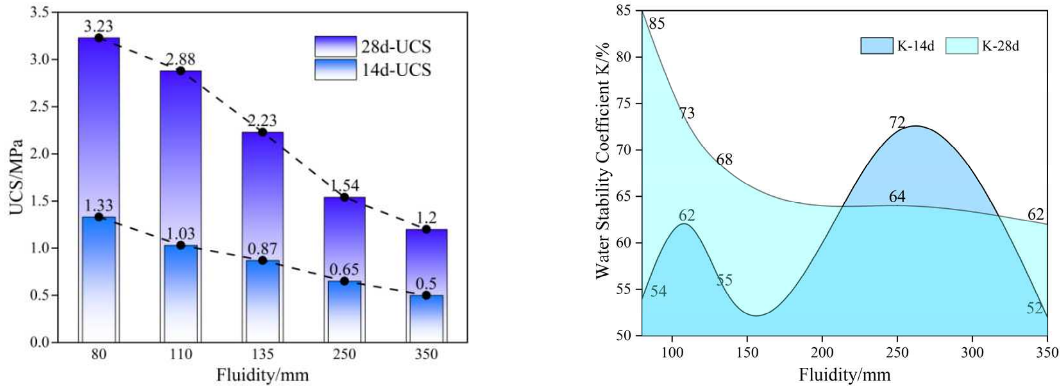
(f) Mass change rate

Figure 5 Mass loss results after wet-dry cycles



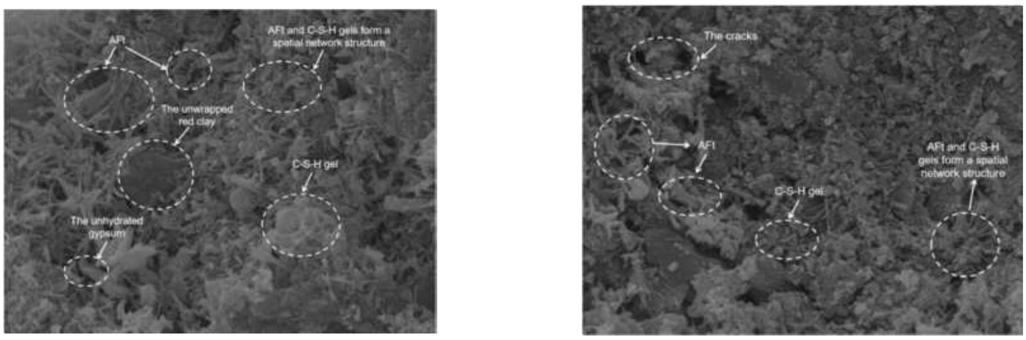
(a) Strength (b) Strength change rate

Figure 6 Influence of wet-dry cycles on the strength of FSR



(a) Flowability vs. UCS (b) Flowability vs. Water Stability

Figure 7 Relationships between flowability, strength, and water stability



(a) 14 days (b) 28 days

Figure 8 SEM results of FSR specimens

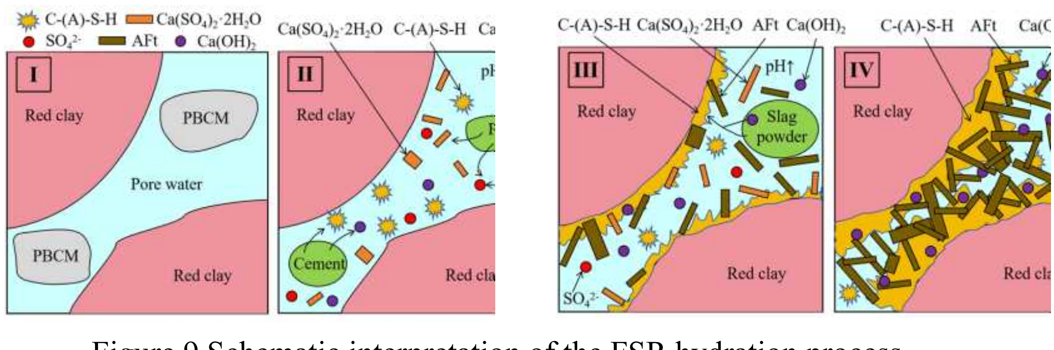


Figure 9 Schematic interpretation of the FSR hydration process

3 Major findings

(1) The fresh fluidized solidified red clay (FSR) mixtures demonstrated acceptable flowability characteristics through adjustments in the water-to-solids ratio (W/S) and/or the incorporation of specific additives. The influence of the cementitious material-to-soil ratio (C/S) on flow behavior exhibited a non-linear trend, peaking at an approximate ratio of 35:65. Furthermore, the inclusion of polycarboxylate-based (PCE) superplasticizer and alkaline lignosulfonate (215F) could effectively facilitate the achievement of the desired flowability for practical applications.

(2) An inverse relationship was observed between the water-to-solids ratio (W/S) and unconfined compressive strength (UCS), while an elevated cementitious material-to-soil ratio (C/S) generally contributed to enhanced strength. Consequently, a C/S exceeding the approximate threshold of 35:65 is recommended for FSR mixtures. The inclusion of additives generally resulted in a reduction in UCS. A comparative analysis revealed that the impact of PCE on strength was comparatively less detrimental, and in certain instances, it may even exhibit a positive influence on strength development.

(3) An increase in the W/S is associated with a decrease in the water stability coefficient K of FSR. The incorporation of additives into FSR generally leads to a reduction in the K, which further declines as the concentration of additives rises. The wet-dry cycle test indicated that after undergoing 5 cycles, the mass of FSR gradually decreased, but it was still able to maintain the mass loss rate within 13.07%. The UCS first decreased, then increased, and then decreased again as the wet-dry cycles progressed, which is related to the erosion of water and the further hydration of PBCM.

(4) Under microscopic observation, FSR contains a large amount of AFt and C-S-H gel. As the curing age increases, the quantity of hydration products increases, leading to a reduction in the internal voids of solidified soil and a consequent densification of the microstructure.

Nondestructive Evaluation of Concrete Permeability and Enhanced Corrosion Resistance via Surface Treatment

Qiao Dong [1]

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Graphical abstract

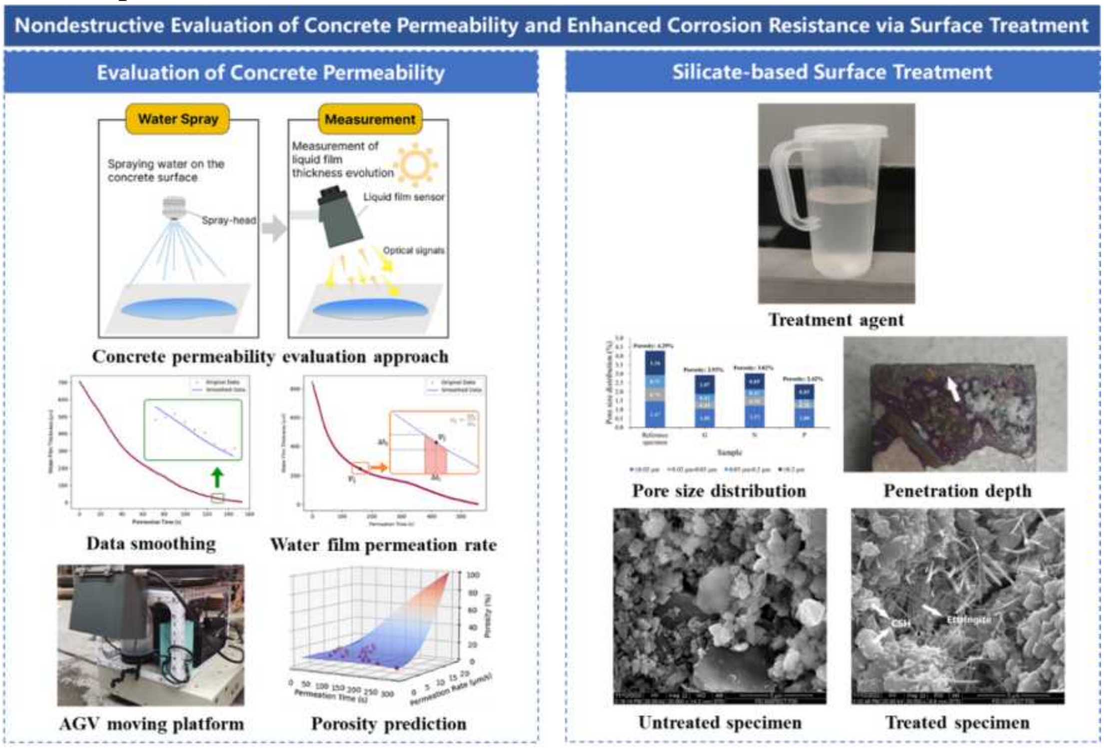


Figure 1 Graphical abstract

1 Objectives and Methodology

This study introduces an innovative in-situ approach for evaluating concrete surface permeability, overcoming the limitations of traditional methods that rely on cored samples or specific locations. The method uses dynamic water film changes to develop a porosity prediction model based on water film thickness and surface porosity. Environmental factors, including temperature, humidity, wind speed, solar radiation, and surface slope, were considered for accuracy. A large-area in-situ testing system was also designed to evaluate permeability across extensive concrete surfaces. Additionally, a composite silicate-based surface treatment was developed to enhance corrosion resistance. Its protective performance was evaluated through freeze-thaw, water impermeability, and carbonation resistance tests on concrete samples of varying strength grades. Nuclear magnetic resonance (NMR) was employed to examine changes in the concrete pore structure, while scanning electron microscopy (SEM) was used to analyze the microstructures.

2 Major results and findings

The study demonstrated a significant correlation between the water film permeation rate and concrete surface porosity. A predictive model based on dynamic water film data effectively forecasted the porosity of concrete surfaces. Temperature, relative humidity, wind speed, solar radiation, and concrete surface slope were identified as key factors influencing the water film permeation rate. The inclusion of correction coefficients for these environmental variables substantially enhanced the accuracy and applicability of the porosity prediction model across diverse conditions.

The in-situ large-area test system, as shown in **Figure 2**, overcome the limitations of traditional methods that rely on core samples or specific testing positions. This innovative system streamlines the permeability evaluation of concrete pavements.

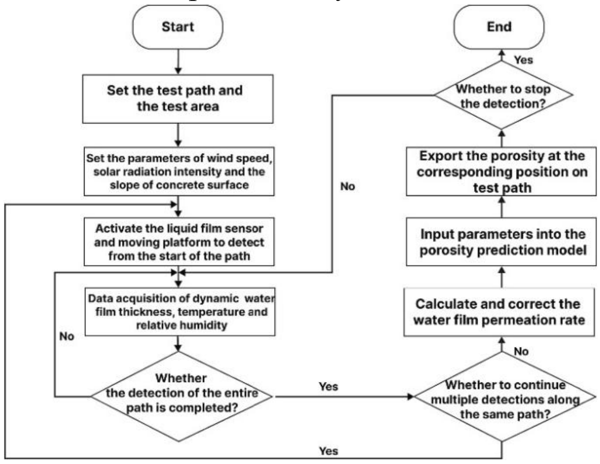
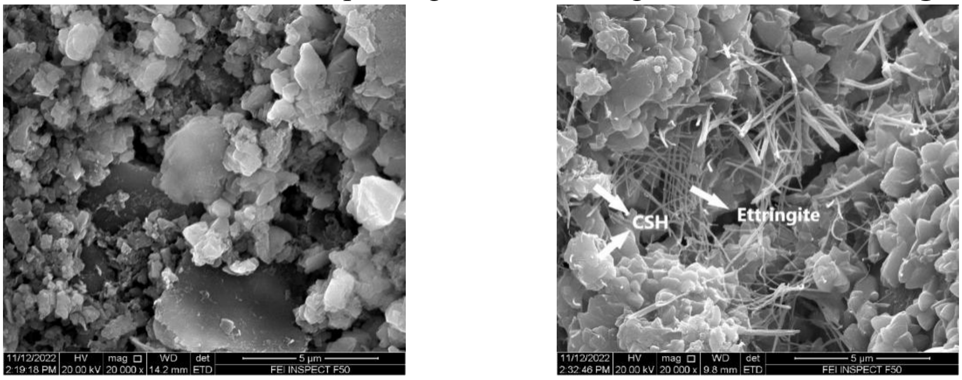


Figure 2 Procedure of large area in-situ test system

The surface treatment significantly reduced the concrete surface porosity, primarily eliminating harmful and highly harmful pores. This material showed superior performance in freeze-thaw resistance, water impermeability, and carbonation resistance. Calcium Silicate Hydrate (CSH) gels, formed through the reaction of silicates and calcium hydroxide, played a crucial role in blocking micropores and microcracks on the concrete surface. The treatment agent also stabilized ettringite within the concrete structure, improving concrete strength, as illustrated in **Figure 3**.



(a) Specimen for reference (b) Treated specimen

Figure 3 SEM images for the untreated and treated specimens

Summary:

This meeting covered three key areas of cement materials research, presenting a range of innovative findings with practical value for the construction sector.

Firstly, research on high-performance materials suitable for extreme conditions was discussed. Dr. Changjun Zhou's BFPMPC mortar performs exceptionally in cold regions with frequent freeze-thaw cycles. By incorporating styrene-butadiene copolymer and basalt fibers, it achieves a 55% improvement in flexural strength and enhanced fracture resistance, addressing the urgent need for rapid repair solutions in cold climates where ice and de-icing salts cause significant material degradation. Dr. Weimin Song's work on semi-flexible pavements (SFP) utilized silane coupling agent KH550 to strengthen the interface between porous asphalt and grout. Tests revealed distinct failure behaviors: brittle fracture at -10°C versus ductile performance at 25°C, making these pavements more adaptable to temperature variations.

Secondly, the focus was on low-carbon materials and waste utilization. Dr. Hao Wu and Dr. Shanshan Jin explored phosphogypsum (PG) applications. PG-modified slope substrates showed a 111% increase in cohesion and optimized pore structure, while PG-cement blends for red clay stabilization met strength requirements with a 35% lower carbon footprint than conventional mixes. Dr. Yongjie Ding developed new geopolymer materials, including PSSB, which reduced heavy metal leaching (21.87% for Ni, 47.32% for Pb) and effectively immobilized fluorine. His firing-free ceramsite from PG-geopolymer composites achieved 92.2% fluorine immobilization, advancing towards zero-waste construction.

Thirdly, smart monitoring and durability enhancement were addressed. Dr. Qiao Dong's non-destructive permeability evaluation system uses dynamic water film metrics to predict concrete porosity, considering temperature and humidity. Combined with silicate treatments, it reduced harmful pores by 50% and improved freeze-thaw resistance by 30%, enabling predictive pavement maintenance and extending service life.

Overall, the meeting showcased cutting-edge research in cement materials, emphasizing innovation, sustainability, and improved performance across diverse applications.

Parallel Session E4

Topic: 3D Printing Materials Innovation and Technical Research for Civil Transportation Infrastructure

Chair: Jie Xu, Professor, Tianjin University
Cochair: Xue Luo, Professor, Zhejiang University; Wen Xu, Postdoc, Taizhou University

Introduction:

Concrete 3D printing technology, a cutting-edge facet of additive manufacturing, is steering the construction industry toward a new era of digital transformation. With its unique advantages—digitization, automation, mold-free construction, low cost, and high precision—this technology is rapidly gaining traction across various sectors, including construction, municipal engineering, roads, bridges, and landscaping, showcasing both remarkable vitality and vast potential.

Nevertheless, the technology remains in its nascent stages and continues to face several challenges, including material selection and composition, equipment design and development, path optimization, product performance, and the establishment of standards and regulations. Key issues such as how to achieve efficient reinforcement placement for enhanced structural performance, how to develop a robust standards system for quality consistency, and how to overcome equipment limitations for large-scale construction printing must be addressed. These challenges necessitate the integration of interdisciplinary research and collaboration to advance concrete 3D printing technology toward higher quality, greater speed, and scientific sophistication.

This conference is designed to unite leading global experts to share cutting-edge research and practical experiences, fostering deeper collaboration between academia and industry. Together, we can explore the boundless potential of this groundbreaking technology and drive the green, intelligent, and sustainable development of the construction industry forward!

Speech:

Research on the 3D Printing Process and Filament Shape of Cementitious Materials in Low Gravity

Song Han, School of Civil Engineering, Beijing Jiaotong University

Research on the Mechanical Behavior of 3D Printed Geopolymer Concrete Containing Waste Ceramic

Jie Xu, School of Civil Engineering, Tianjin University

Research on the Interface Bonding performance of LC3 cement and Expanded clay aggregate in Coal-based solid waste concrete

Yu Yang, Yaoyu Wang, School of Civil Engineering, DaLian University

Performance and design methodology of the reinforced 3D printed concrete beams

Qiang Wang, School of Civil and Transportation Engineering, Hebei University of Technology

Research on Pore Characteristics of 3D Printing Carbon Fiber Reinforced Green Concrete

Wen Xu, College of Civil and Architectural Engineering, Taizhou University

Research on the 3D Printing Process and Filament Shape of Cementitious Materials in Low Gravity

Song Han [1]

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Graphical abstract

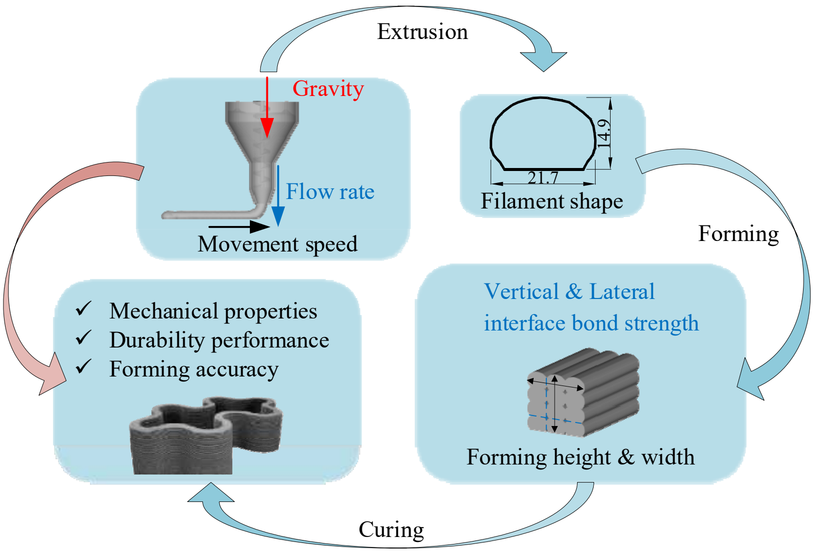

Figure 1 Graphical abstract

1 Objectives and Methodology

3D printing construction with cementitious materials is a crucial technology for realizing future outer space construction. During the printing process, the printing cementitious materials is extruded from the nozzle following the designed path, forming filaments. Low gravity environments significantly affect the extrusion of the 3D printing slurry and the stacking process of the filament formation. This paper focuses on the changes in filament shape of 3D printing cementitious materials in different gravity. Experiments on 3D printing under low gravity were conducted by printing cementitious materials in a liquid medium, using buoyant force to offset part of the gravity. Based on Computational Fluid Dynamics (CFD) methods, a numerical model of the 3D printing forming process for cementitious materials was established. Two parameters, the cross-sectional area and the aspect ratio, were established to quantify the characteristics of the filament cross-sections. The shape differences between the filaments were defined by the cross-sectional variation coefficient, and the accuracy of the model's computational results was validated through the comparison of experimental and simulated data. By controlling the spiral rotation speed, the movement speed of the printer, and modifying the gravity parameters, the research examined the patterns of influence exerted by different gravity on the shape of the filaments. Additionally, based on the results of fluid dynamics calculations, the mechanism of changes in filament shape under the combined effects of gravity and printing parameters was elucidated. The findings of this research will provide valuable information for avoiding printing failures and ensuring stable filament formation during low gravity 3D printing processes. It will also provide practical theoretical principles for the development of low gravity 3D printers, and the selection of printing parameters and materials.

2 Major results and findings

(1) Utilizing liquid buoyant force to offset part of gravity effectively simulates low gravity for conducting filament formation experiments in 3D printing. In conjunction with CFD software, this approach can effectively analyze the printing process of cementitious materials under low gravity conditions and predict the shape of the filaments.

(2) In low gravity conditions, with other printing parameters remaining constant, the aspect ratio of the filament cross-section is greater than that in Earth gravity printing. The influence of printing parameters on the extrusion process and filament shape was basically the same in low gravity and Earth gravity conditions.

(3) In a low gravity printing environment, the precision control of a piston extrusion 3D printer is superior to that of a spiral extrusion 3D printer.

(4) When using a spiral extrusion 3D printer in a low gravity environment, the range of yield stresses of the slurry that can be printed varies with different gravity value.

Research on the Mechanical Behavior of 3D Printed Geopolymer Concrete Containing Waste Ceramic

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Graphical abstract

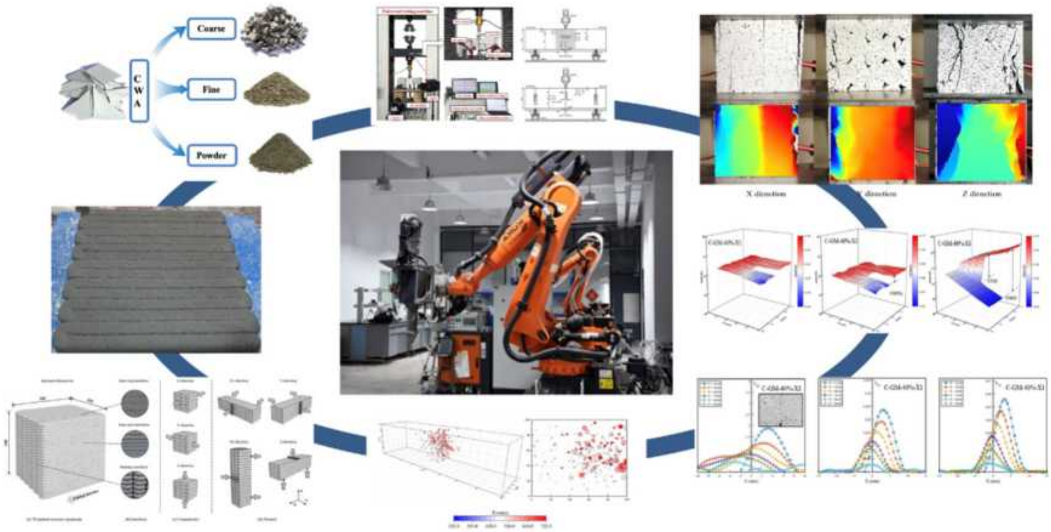

Figure 1 Graphical abstract

1 Objectives and Methodology

This study systematically investigates the fracture behavior of 3D printed geopolymer concrete containing waste ceramic. Based on three-point bending tests, the effect of waste ceramic aggregate (CWA) content and printing direction on the cracking patterns of 3D printed geopolymer concrete (3DGPC) were investigated with the help of digital image correlation (DIC) and acoustic emission (AE) techniques. The test results showed that the addition of 40% CWA significantly enhanced the mechanical properties, fracture toughness and fracture energy of concrete. Compared to inter-strip cracking, inter-layer cracking was verified to be more effective in mitigating stress concentrations which further improves the performance of concrete. DIC analysis revealed that CWA incorporation and interlayer fracture had significantly increased the crack opening displacement, effectively inhibiting crack propagation and alleviating stress concentration at the crack tip. AE analysis further indicated that the incorporation of CWA and interlayer fracture can reduced shear cracks and enhanced the fracture toughness effectively. This research not only provides optimal mix proportions and printing parameters for 3D printed geopolymer concrete, but also holds the potential to promote the sustainable development of 3D printing technology.

2 Major results and findings

This study investigated the effects of CWA content and printing direction on the fracture behavior of 3DGPC incorporating waste ceramics. The specific conclusions are as follows:

(1) With the CWA content of 40%, the compressive strength, flexural strength, fracture energy, and fracture toughness of 3DGPC were significantly enhanced. The reason can be attributed to the rough surface and good water absorption of CWA, which enhanced the bond strength between the aggregate and the matrix, and the multi-angled shape of CWA potentially improved the material's toughness. Additionally, the reactive pozzolanic components in CWA induced secondary hydration reactions within the matrix, thereby positively influencing the overall material properties.

(2) Compared to interstrip fracture (X1 and X2 directions), interlayer fracture (Y and Z directions) exhibited superior fracture toughness, fracture energy, and load-bearing capacity. This is due to the interlayer fracture process, where cracks propagate along the interlayer interface, absorbing more energy and effectively dispersing stress concentration, thereby enhancing the overall toughness of the material.

(3) The dynamic process of crack propagation can be precisely captured by DIC technology, revealing that the incorporation of CWA and interlayer fracture significantly increased the crack opening displacement value, effectively inhibited crack propagation, and alleviated stress concentration at the crack tip, further confirming the enhancement of the material's fracture toughness.

(4) The activity pattern of microcracks during crack propagation can be effectively revealed based on the analysis of AE parameters, indicating that the incorporation of CWA and interlayer fracture resulted in a relative reduction in shear cracks, manifesting the ductile characteristics of the material. Meanwhile, the decrease and reduced variation in *b*-value, along with the localization of AE sources, reflected the presence of microcracks leading to the bifurcation of the main crack, increasing the energy requirement for crack propagation, and effectively enhancing the material's fracture toughness.

Research on the Interface Bonding performance of LC3 cement and Expanded clay aggregate in Coal-based solid waste concrete

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Graphical abstract

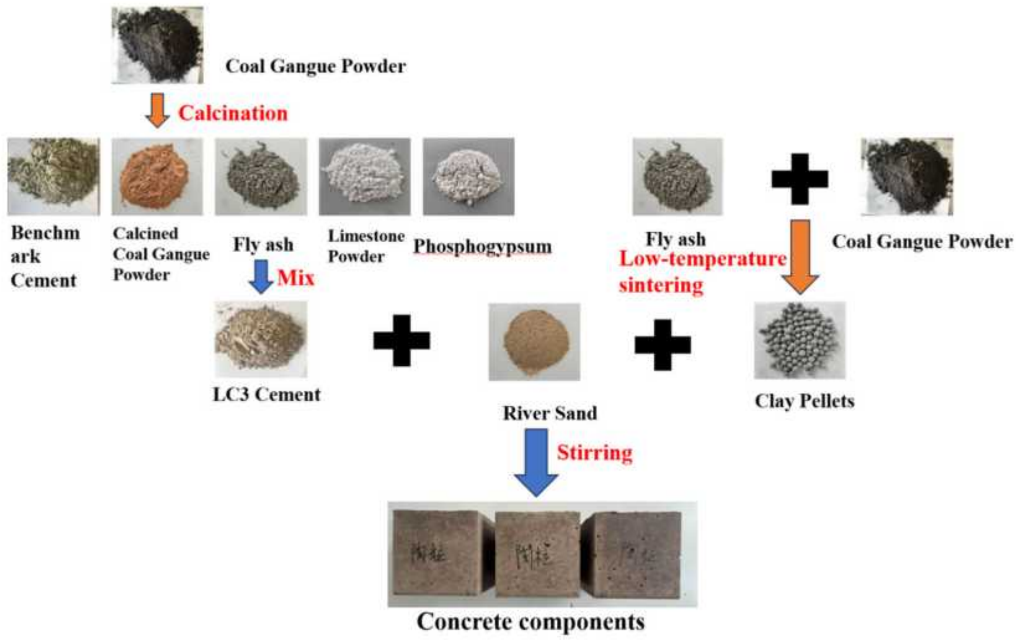

Figure 1 Graphical abstract

1 Research Objectives and Methods

To improve the resource utilization efficiency of coal-based solid waste, this study investigates the high-value conversion pathways for aluminosilicate minerals in coal gangue: an activated calcination process is employed to transform into a core component of high-performance LC3 cement (a ternary system incorporating fly ash, activated coal gangue, and Portland cement). Due to its low-carbon attributes (reducing CO_2emissions by 30%－50%) and exceptional durability, this approach drives the development of green building materials. Furthermore, lightweight ceramsite, sintered from coal gangue, is utilized as an aggregate. When combined with LC3 cement to form concrete, an overall CO_2reduction of 60%－80% can be achieved. However, the structural weakness of the interfacial transition zone (ITZ) between the ceramsite and LC3 matrix significantly compromises the material's performance. Thus, It is imperative to reveal the bonding mechanism to overcome this technical bottleneck.

2 Major Results and Findings

(1) To optimize the pretreatment process and mix proportion of raw materials to enhance the performance of coal-based solid waste-derived LC3 cement. By leveraging the stable hydration products formed between activated coal gangue and fly ash, as well as between phosphogypsum and cement clinker, this research integrates the inherent properties of each material. Through optimizing key technical parameters and elucidating the mechanisms at each stage, it achieves sequential conversion and preparation of LC3 cement from coal gangue. T

his approach significantly enhances the comprehensive utilization rate of coal gangue while successfully developing a high-performance, low-cost product.

(2) **Optimize the pretreatment process and mix proportion of raw materials, and utilize coal gangue, fly ash, and composite additives to prepare ceramsite via low-temperature sintering, thereby further improving solid waste utilization efficiency.**

(3) The use of LC3 cement as a partial replacement for clinker, combined with ceramsite as a lightweight aggregate, can reduce the overall CO_2 emissions of concrete by 60%–80%. Compared to conventional cement, the micro-filling effect of fly ash and the pozzolanic activity of activated coal gangue in LC3 may uniquely influence the structure of the interfacial transition zone (ITZ). Therefore, this study investigates the interfacial bonding between ceramsite and the LC3 matrix, along with the mechanical and durability properties of the resulting concrete.

Performance and design methodology of the reinforced 3D printed concrete beams

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1 Objectives and Methodology

A review of current research revealed that the 3DPC truss configuration design is primarily based on either geometry-driven approach or stress-driven approach. The former is often obtained without considering the actual load transfer paths within the truss struts and ties, and may fail to bring the light-weight deign advantage using 3D printing technology into full play. Conversely, in the truss configuration derived from a stress-driven approach, such as topology optimization, significant concrete savings can be realized by removing inefficient stress-transfer elements while retaining those that are most effective in bearing loads. Though experimental investigations into topology optimization design methods have been recently conducted, the performance evaluation for the reinforced structures was scarcely reported due to the absence of appropriate reinforcement design approach, posing great uncertainties for the confident utilization of the reinforced 3DPC truss beam. To tackle this challenge, it is crucial to integrate a rational reinforcement design concept into the design for the topology optimization-based reinforced 3DPC trusses to optimize material distribution, achieve lightweight structural forms, and enhance the load transfer efficiency.

This research therefore presents and validates a workflow for designing and optimizing a reinforced 3DPC truss beams to compensate for the current research gaps. The paper layout is as follows. In Section 2, the workflow was proposed to guide the reinforcement and performance design for the topology optimization-based reinforced 3DPC truss beam. Section 3 reported the procedure of topology optimization-based 3DPC truss configuration generation and provided a numerical example. Sections 4 and 5 introduced the local reinforcing bar selection and the overall reinforcement strategy, as well as structural testing results for the topology optimization-based reinforced 3DPC truss beams. Subsequently, Section 6 developed a refined 3D finite element model (FEM) for the topology optimization-based reinforced 3DPC truss beams under three-point bending to help understand its failure mechanism. Section 7 conducted a parametric investigation of the reinforced 3DPC truss beams via the validated analysis to optimize its design. Finally, Section 8 summarizes the key findings and provides further recommendations.

2 Major results and findings

(1) The truss configuration optimization process, which incorporates 3DPC additive constraints into SIMP method, allows for truss beams with efficient load transfer paths and reduced material usage. Additionally, the graph-driven approach supports single-stroke toolpath planning, ensuring precise fabrication of intricate 3DPC truss configuration.

(2) The proposed criterion for selecting reinforcing bars takes into account the impacts of parameters such as bar rib height, bar diameter, 3DPC cover thickness, and

embedment length, on the bond performance between the reinforcing bar and 3DPC. By applying this criterion, the characteristics of the reinforcing bar can be optimized to achieve the desired failure mode. As more experimental data becomes available, both the coefficients in the criterion and its mathematical formulation will be further refined for greater accuracy.

(3) The failure of reinforced 3DPC truss beams progresses through elastic, elastic-plastic, post-yield, and local failure stages. Local failure arises from inadequate reinforcement in external compression struts. While truss reinforcements do not impact stress transfer under low loads, extensive 3DPC cracking can disrupt the ideal stress distribution.

(4) The introduction of the surface-based cohesive model with the CDP model accurately captures the flexural behaviors of reinforced truss beams. The 3DPC tension damage evolution obtained from the numerical results has clearly revealed the stress transfer path at different stages, which conforms well to the experimental phenomenon.

(5) Increased material volume delays local failure and boosts beam ductility, while higher 3DPC strength minimizes fractures and extends failure displacement without compromising load-bearing capacity. Reinforcement content and strength are crucial for beam performance. Notably, the beams designed through the stress-driven workflow boost strength-to-weight ratios by 48% to 94% while maintaining a comparable deflection-to-weight ratio to the RC beam.

Research on Pore Characteristics of 3D Printing Carbon Fiber Reinforced Green Concrete

Wen Xu [1]

[1] College of Civil and Architectural Engineering, Taizhou University, Taizhou 318000, China.

Graphical abstract

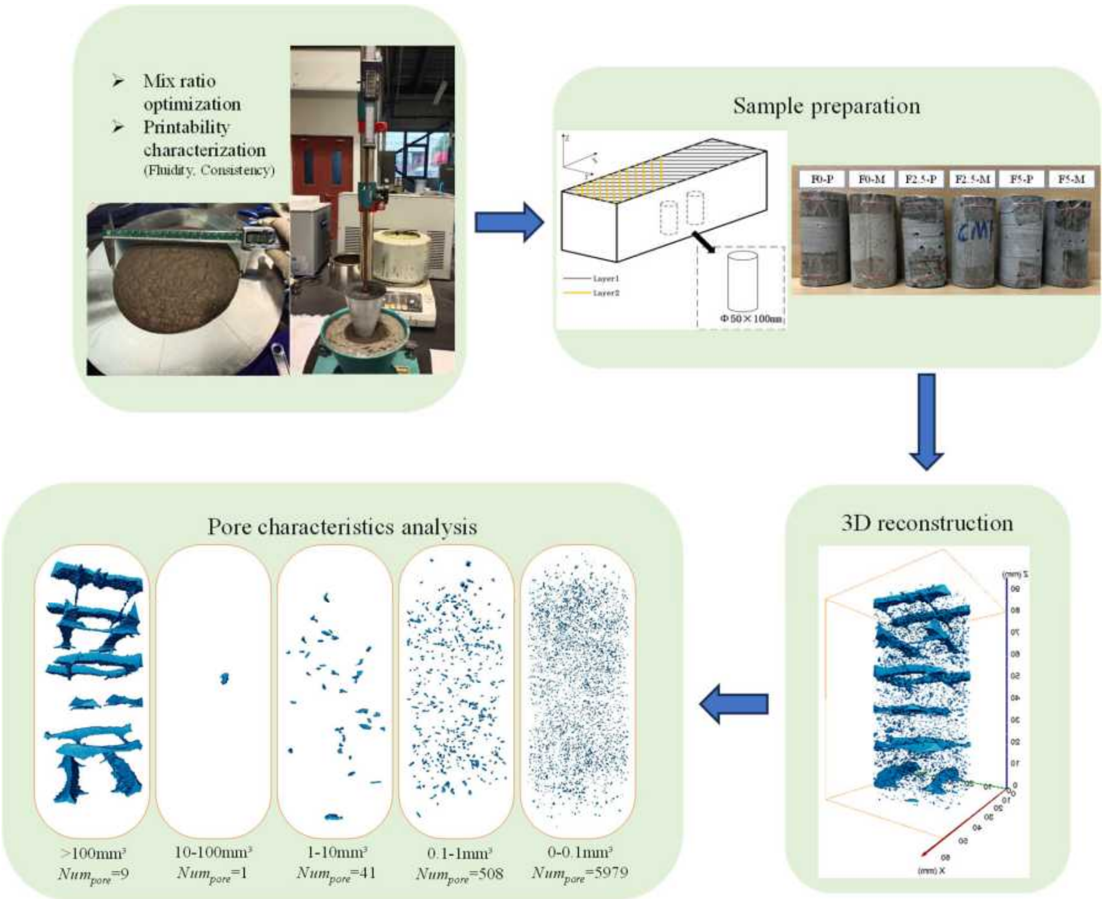

Figure 1 Graphical abstract

1 Objectives and Methodology

Concrete 3D printing technology is an innovative application that integrates 3D printing techniques with concrete materials. This technology combines digital design with intelligent construction methods, enabling the high-precision fabrication of complex structures through layer-by-layer material deposition. The pore characteristics of 3D printed concrete play a significant role in influencing its mechanical properties and durability. In this study, X-ray computed tomography (CT) and mercury intrusion porosimetry (MIP) were employed to examine the pore characteristics of both 3D printed concrete specimens and mold-cast concrete specimens at three different mix ratios. The study covered a wide range of pore sizes, from "nanometer-scale gel pores" to "centimeter-scale printing voids." A custom MATLAB program was used to process CT scan images and extract 2D pore feature data. Avizo software facilitated the 3D reconstruction of concrete specimens, enabling the three-dimensional visualization and extraction of pore characteristics. The study further analyzed how these pore characteristics affect the material's overall performance.

2 Major results and findings

(2) The results from the two-dimensional pore feature analysis indicate that, in the absence of ground carbon fibers, the number and porosity of the two-dimensional pores in the 3D printed samples—varying with sample height—are higher than those in the mold-cast samples. However, when ground carbon fibers are added, the number of two-dimensional pores in the 3D printed samples, which also varies with sample height, is lower than that observed in the mold-cast samples.

(3) The three-dimensional reconstruction results reveal that, without ground carbon fibers, both the total number and porosity of the pores in the 3D printed samples are higher than in the mold-cast samples. Upon the addition of ground carbon fibers, however, the total number of pores in the 3D printed samples is lower than that in the mold-cast samples.

(3) An irregularity calculation formula was proposed to assess the irregular shape of pores. This formula was used to calculate the irregularity of pores with volumes greater than 10 mm^3 in the six samples. The results show that the irregularity of large pores in the 3D printed samples is approximately 15 times greater than in the mold-cast samples.

(4) The connectivity of inter-layer voids in the 3D printed samples was also examined, revealing that two strip-like printing voids could merge to form a larger void.

(5) Additionally, a supplementary study using mercury intrusion was conducted to analyze gel pores at the nanometer scale and micron-scale pores in the six samples. This study demonstrated that gel pores with diameters between 7 and 11 nm were the most developed and represented the largest proportion of the microscopic pores across the six samples.

Parallel Session E4 Summary:

This session explored key challenges in concrete 3D printing:

(1) Material Challenges: Materials must balance extrudability, buildability, and final performance. Key issues include anisotropy, weak interlayer bonding, shrinkage cracking, and limited durability in extreme environments.

(2) Design and Evaluation Challenges: Anisotropy and heterogeneity complicate structural design, and traditional methods are inadequate. Reinforcement integration remains difficult, while non-destructive testing struggles to assess layered structures. Long-term performance data is scarce.

(3) Process and Equipment Challenges: Major issues include maintaining print accuracy for large structures, balancing speed with precision, limited scalability of equipment, and technical difficulties in multi-material printing.

(4) Standardization and Industrialization Challenges: Lack of unified standards hinders consistency and recognition. High costs and low industry acceptance due to conservatism also impede adoption, despite potential formwork and labor savings.

Based on conference discussions, concrete 3D printing will advance in four key directions:

(1) Material Innovation: Emphasis will be on green materials like geopolymer and LC3 low-carbon cement to reduce environmental impact. Multifunctional materials, including self-healing and self-cleaning concrete, will expand structural capabilities. Waste utilization will broaden to incorporate fly ash, slag, and construction waste, supporting a circular economy.

(2) Smart Processes & Equipment: AI and machine learning will enable real-time monitoring and adaptive control, improving accuracy. Large-scale and multi-material printing technologies will evolve, allowing complex, graded material structures. Multi-robot collaboration will enhance efficiency and enable sophisticated designs.

(3) Extreme Environment Applications: The technology will be deployed in challenging settings such as marine and underwater construction, extraterrestrial building (lunar/Mars bases), polar stations, and disaster relief shelters.

(4) Standardization & Collaboration: Efforts will accelerate to establish unified standards for materials, design, and construction. Industry-academia-research integration will strengthen, fostering interdisciplinary cooperation to overcome technical barriers and promote application.

The conference successfully showcased the latest research achievements and development trends in the field of concrete 3D printing technology. Five thematic reports demonstrated the progress of this technology in material innovation, process optimization, structural design, and performance evaluation from different perspectives, revealing the trend of concrete 3D printing technology transitioning from laboratory research to engineering applications. The conference highlighted the main challenges currently faced by the technology, including material anisotropy, insufficient interlayer bonding strength, lack of standardized design methods, limitations in printing processes, and industrialization barriers. These challenges require joint efforts from global research institutions and companies to overcome through interdisciplinary collaboration and industry-research synergy. In the future, concrete 3D printing technology will develop toward green and low-carbon solutions, intelligence, multifunctionalization, and applications in extreme environments, providing key technical support for the digitalization, greening, and sustainable development of the construction industry. Through continuous technological innovation and industry collaboration, concrete 3D printing technology is expected to fundamentally transform traditional construction methods and drive the construction industry toward greater efficiency, energy savings, and environmental sustainability.

Parallel Session F4

Topic: Leading International Experts Commentary on Transportation Infrastructure

Graduate Students Presentations

Host: You Zhan, Associate Professor, Southwest Jiaotong University; Haibo Ding, Associate Professor, Southwest Jiaotong University

Experts: Xingyi Zhu, Professor, Tongji University; Yuhong Wang, Professor, Hong Kong Polytechnic University; Meng Ling, Professor, Beijing University of Civil Engineering and Architecture; Baoshan Huang, Professor, University of Tennessee, Knoxville

Speech:

Influence of Asphalt Binder Performances on Thermal Shrinkage Performance of Asphalt Mixtures

Ziyu Bai, Chongqing Jiaotong University

Effects of Freeze-Thaw Cycles on Fatigue Performance of Asphalt Mixture and a Fatigue-Freeze-Thaw Damage Evolution Model

Xin Li, Inner Mongolia University Of Technology

Effects of Hazardous Spills by Road Accidents on Pavement Texture and its Deterioration Mechanism

Zhenlong Gong, University of Science and Technology Beijing

Long-Chain Alkyl Emulsifiers Induced Asphalt Particle Dispersion: Lipophilicity-Enhancement Effect

Songxiang Zhu, Chongqing Jiaotong University

Investigation of the Topological Characteristics of Force Chain Network in Aggregate Blend Using Discrete Element Method and Complex Network Theory

Weixiao Yu, University of Science and Technology Beijing

Cracking Characteristics of Warm-Mix Recycled Fiber Asphalt Mixture under Mode I, Mode III, and Mixed-Mode I/III Based on Acoustic Emission Technology

Zhiqiang Liu, Inner Mongolia University of Technology

Research on Rutting Prediction Model and Characteristics of Full-Scale Asphalt Concrete Pavement Based on Data-Driven Method

Pengpeng Li, University of Science and Technology Beijing

Study on the Low-Temperature Cracking Characteristics of Warm-Mix Steel Slag and Rubber Powder Modified Asphalt Mixtures Based on Acoustic Emission Technology

Die Hu, Inner Mongolia University of Technology

Application of Explicit Analysis Methods in Dynamic Response Analysis of Asphalt Pavements under Traffic Loading

Xiangrui Han, University of Science and Technology Beijing

Quantitative Characterization and Stochastic Generation Methods for Three-Dimensional Morphology of Aggregates

Yawen Shang, University of Science and Technology Beijing

A Study on the Microscopic Contact Characteristics of Tire–Pavement Interaction Considering Multiple Factors

Yiting Liu, University of Science and Technology Beijing

Multi-Source Data Processing and Analysis for Intelligent Compaction of Asphalt Pavements

Yingjun Bao, University of Science and Technology Beijing

Research on Maintenance Decision-Making Method Based on Evaluation Index of Longitudinal Cracks on Expressways and Road Surface Material Tests

Zhisheng Han, University of Science and Technology Beijing

Parallel Session G3

Topic: Enhancing the Resilience of Bridge Structures to Extreme Events

Chair: Xiaoyi Zhou, Professor, Southeast University
Cochair: Kang Gao, Professor, Southeast University; Rujin Ma, Professor, Tongji University
Speech:
A Material-Structure Integrated Design Method for Textile Composite Fire-Resistant Protection of Bridge Structural Cables Subjected to Vehicle-Induced Fires
Xiaoyi Zhou, Professor, Southeast University
Numerical Investigation into Assessment of Post-Blast Damage to Steel Box Girder under Vehicle Fire
Rujin Ma, Professor, Tongji University
Finite Element Method-Based Data-Driven Multi-Damage Detection Methods for 1D and 2D Bridge Models: Theoretical and Experimental Studies
Kang Gao, Professor, Southeast University
Study on Optimal Seismic-Resistant System and Seismic Resilience Enhancement Strategies for Long-Span Self-Anchored Suspension Bridges with Twin Towers and Spatial Cable Planes
Hui Qu, Senior Engineer, Tongji Architecture Design (Group) Co. Ltd.
Effect of Fire Insulation on Fire Performance of the Concrete Beams Strengthened With the CFRP Sheets Pasted by Magnesium Phosphate Inorganic Adhesive
Pengfei Ren, Associate Professor, Shandong Jianzhu University

Parallel Session G4

Topic: Constructing Green Technology Systems for Road Engineering

Chair: Jiangmiao Yu, Professor, South China University of Technology Cochair: Wanqiu Liu, Professor, Hainan University

Speech:

Development on Low-Noise Friction Course with New Thinking & Application

Jiangmiao Yu, Qitai Weng, and Yuxun Zou, School of Civil Engineering and Transportation, South China University of Technology

Synergistic Utilization of Steel Slag Coarse and Fine Aggregates in Asphalt Mixture: Durability and Life-Cycle Carbon Emission Evaluation

Zongwu Chen, Yue Xiao, Zhen Leng, Shaopeng Wu, Tong Zhong and Zhenlong Gong, School of Materials Science and Engineering, Chang'an University

Influence of compatibility between light oil and isocyanate compounds on rejuvenation properties and mechanisms of aged SBS modified bitumen

Chengwei Xing, Bohan Zhu, Haozongyang Li, Key Laboratory for Special Area Highway Engineering of Ministry of Education, Chang'an University

Development on Low-Noise Friction Course with New Thinking & Application

Jiangmiao Yu [1,2,3], Qitai Weng [1], and Yuxun Zou [1]

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[3] Central Fortune Creation Technology Group Co., Ltd, Foshan 528200, China

1 Objectives of this research

Traffic noise, predominantly tire-pavement noise[1], challenges China's urban infrastructure development. While porous asphalt pavements offer source-level noise reduction, clogging rapidly diminishes noise reduction and durability[2]. To achieve long-term noise reduction, this study developed a novel low-noise friction course. By optimizing surface texture, enhancing damping performance, and using advanced asphalt materials, it simultaneously improves noise reduction and durability.

2 Methodology and main research work

2.1 Methodology

This study reduced the Nominal Maximum Aggregate Size (NMAS) to 8, 5, and 3 mm, using the Coarse Aggregate Void Filling (CAVF) method for gradation design. This optimize macro-texture and generate abundant negative texture. GT-TECH high-viscosity & high-elasticity modified asphalt was applied with >15 μm film thickness, enhancing damping performance. Noise reduction mechanisms (texture & damping) were revealed and noise reduction validated via FEM/field tests.

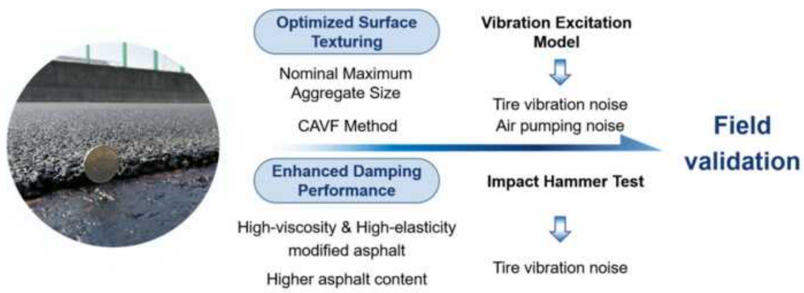


Figure 1 Research roadmap

2.2 Main research work

Laboratory results as shown in Tables 1 and 2, the vibration excitation and noise sound pressure level(SPL) decrease as NMAS reduces. GT's abundant negative texture also yields lower high-frequency noise than GAC-13 with higher S_{sk}.

Table 1 Result of surface texture analysis

	GT-8	GT-5	GT-3	GAC-13	SMA-13
Vibration Excitation/mm	0.78	0.75	0.52	0.89	1.03
S_{sk}/mm	-0.9	-1.2	-1.1	-0.2	-0.9
Nosie SPL/dB(A)	84.97	83.69	81.34	88.99	87.42

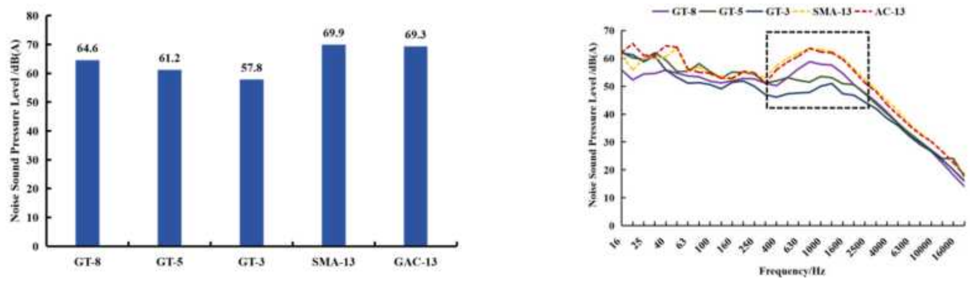
2kHz Noise SPL/dB(A)	36.1	31.3	34.8	38.2	36.8

As show in Table 2, GT's thicker asphalt film gives its damping comparable to AR-SMA-13 and higher than SMA-13. This provides equivalent functionality to crumb rubber, absorbing/ dissipating tire impact energy, reducing noise.

Table 2 Result of impact hammer test

	GT-8	GT-5	GT-3	AR-SMA-13	SMA-13
Damping Ratio	0.0615	0.0611	0.0607	0.0608	0.0555
Asphalt Film Thickness/μm	16.79	16.25	17.69	8.81 (Rubber Content:3%)	8.93

Field results as shown in Figure 2. Comparing GT's noise levels with other pavements, it significantly reduced noise, especially at mid-low frequencies. The application performance measured by Statistical Pass-By (SPB) and Coast-By (CB) is in Table 3 and Figure 3.

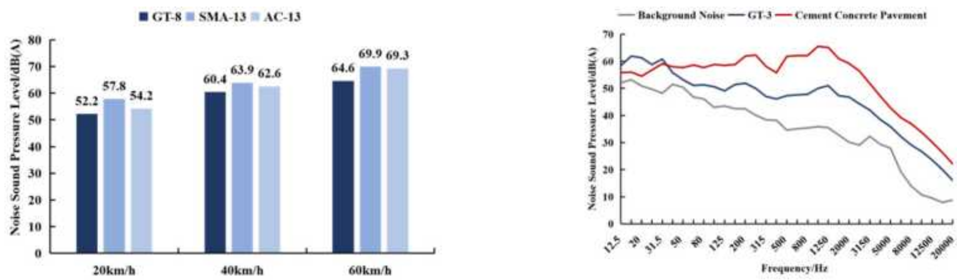


(a) (b)

Figure 2 Test results of tire-pavement noise for different asphalt pavements

Table 3 Result of field validation

	Type	Noise Reduction Performance	Method
Desheng Bridge	GT-8	>10 dB(A) reduction sustained 2 years	SPB
Guangming Bridge	GT-8	7.7 dB(A) noise reduction	SPB
Shunde Bridge	GT-8	5.3 dB(A) noise reduction	CB
Sixiang Road	GT-3	Noise reduction consistently over 10 dB(A)	CB



(a) Shunde Bridge (b)Sixiang Road

Figure 3 Field test results before and after construction

3 Major findings

(1) GT low-noise friction course significantly improving noise reduction performance and durability by optimizing surface texture and damping performance.

(2) Compared to conventional asphalt pavements, GT low-noise friction course reduces noise by 5-12 dB(A), particularly effects on mid-to-low frequency noise.

(3) GT low-noise friction course have been widely implemented, demonstrating remarkable noise reduction performance. It remains consistent over two years.

Synergistic Utilization of Steel Slag Coarse and Fine Aggregates in Asphalt Mixture: Durability and Life-Cycle Carbon Emission Evaluation

Zongwu Chen [1,2], Yue Xiao [1], Zhen Leng [3], Shaopeng Wu [4], Tong Zhong [2] and Zhenlong Gong [2]

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Graphical abstract

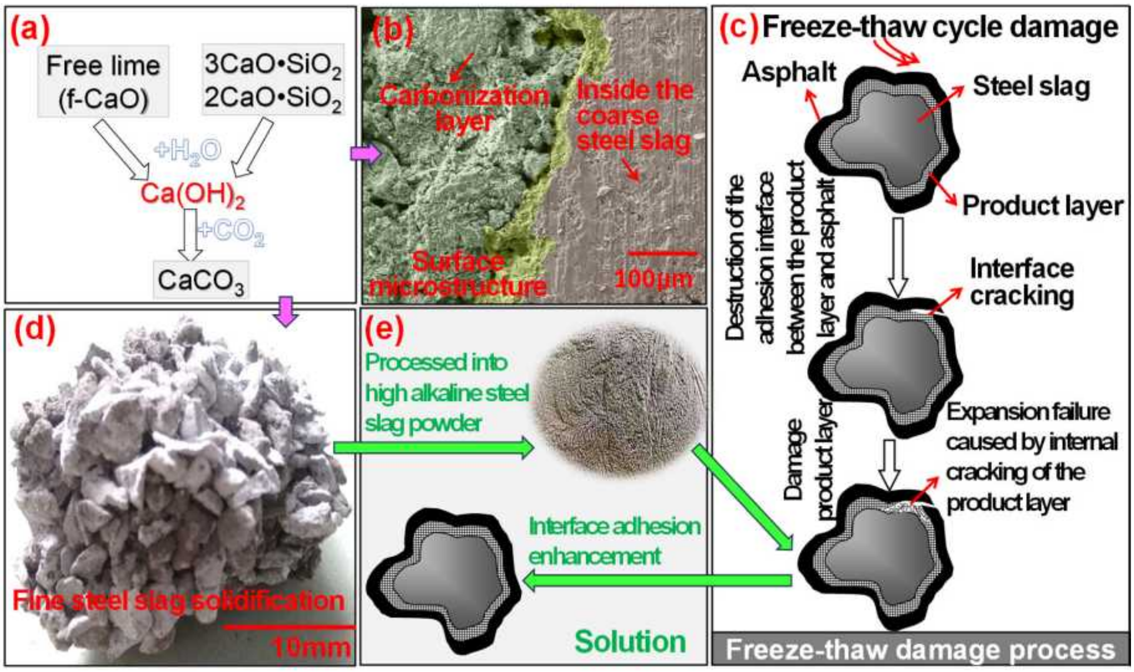


Figure 1 Graphical abstract

1 Objectives and Methodology

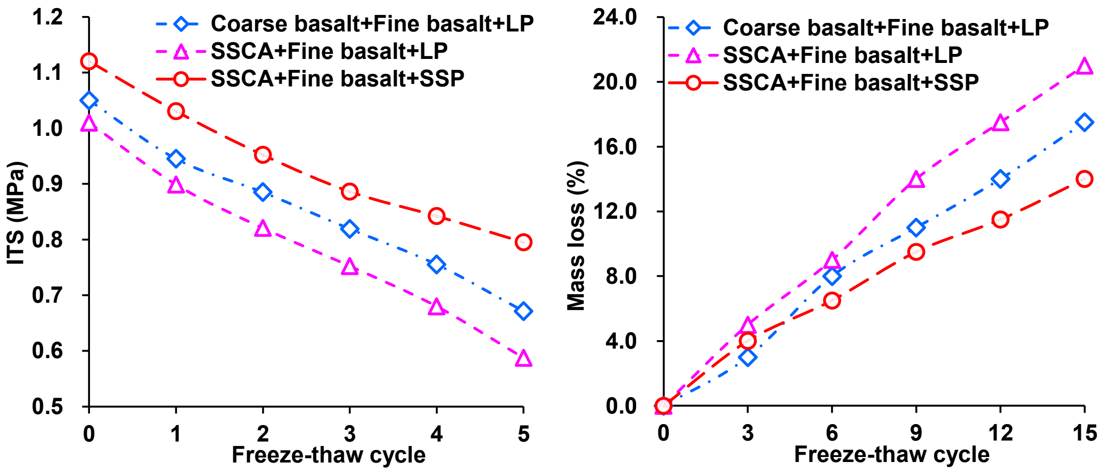
Since steel slag contains minerals such as free calcium oxide, tricalcium silicate, and dicalcium silicate, it inevitably undergoes spontaneous carbonation reactions during storage. During the carbonation of steel slag coarse aggregates (SSCA), a carbonated layer forms on their surface, and this layer is sensitive to damage from freeze-thaw cycles. Meanwhile, the carbonation process causes steel slag fine aggregates (SSFA) to solidify and agglomerate, losing their original particle gradation and thus making them unsuitable for direct use as fine aggregates. Therefore, improving the freeze-thaw durability of asphalt concrete containing SSCA and developing appropriate recycling technologies for SSFA are key to achieving full particle size utilization of steel slag.

To realize the synergistic utilization of steel slag coarse and fine aggregates in asphalt concrete, this study further processes the agglomerated and solidified SSFA into steel slag powder (SSP). Due to the high alkalinity characteristics of steel slag, alkaline SSP can theoretically improve the adhesion performance between SSCA and asphalt mastic, making their bonding interface stronger. It not only enhances the freeze-thaw durability of SSCA but also effectively utilizes the solidified and agglomerated SSFA, achieving 100% utilization of both steel slag coarse and fine aggregates in asphalt concrete. Additionally, the carbon emission behavior of steel slag asphalt concrete is evaluated.

The durability of asphalt concrete incorporating SSCA and SSP prepared by crushing and grinding SSFA was investigated based on indirect tensile strength (ITS) loss and mass loss of Marshall specimens under cyclic freeze-thaw damage. Carbon emission characteristics of steel slag asphalt concrete was evaluated based on material life cycle assessment (LCA) method, and a 1km asphalt pavement consist of 4cm SMA surface layer, 6cm AC middle layer and 8cm AC lower layer) is taken as the functional unit.

2 Major results and findings

SSP has significantly enhenced the durability of asphalt concrete with SSCA under cyclic freeze-thaw damage. As shown in Fig. 2(a), compared with common asphalt concrete containg basalt aggregate and limestone powder (LP) filler (A0) and asphalt concrete with SSCA, fine basalt and LP (A1), asphalt concrete incorperating SSCA, fine basalt and SSP (A2) possesses 6.7% and 10.9% higher original ITS. When cyclic freeze-thaw damage is applied, A2 still holds larger ITS. Compared with A0 and A1, the ITS of A2 is 18.5% and 35.4% bigger after freeze-thaw damage for 5 cycles. At this moment, the ITS loss of A0, A1 and A2 is 36.1%, 41.9% and 29.0% respectively. It proves that SSP both strengthens the ITS and freeze-thaw durability of asphalt concrete incorperating SSCA. The mass loss results of asphalt concrete specimens also support the conclusion. As shown in Fig. 2(b), in the early stage of freeze-thaw damage, there is not much difference in the mass loss of the three asphalt concrete specimens. However, as the degree of freeze-thaw damage increases, the difference in mass loss gradually widens. After freeze-thaw damage for 15 cycles, mass loss of A0, A1 and A2 reaches 17.5%, 21.0% and 14.0%, respectively.



(a) ITS (b) Mass loss

Figure 2 ITS and mass loss of asphalt concrete after freeze-thaw damage

SSP has also reduced the carbon emission of asphalt pavement during its life cycle. As shown in Fig. 3, for natural aggregate asphalt concrete, the total emissions of producing coarse aggregate and filler account for 34.86%, 25.33%, and 27.54% in

SMA13, AC20 and AC25, respectively. For steel slag asphalt concrete, these values are 6.04%, 8.61%, and 9.50%, respectively. It indicates that introducing SSCA and SSP into asphalt concrete can effectively reduce carbon emissions during the production stage of raw materials. Fig. 4 suggests that the service and maintenance stage releases the most carbon, followed by the material production stage in the life cycle of asphalt pavement. Compared with common natural aggregate asphalt pavement, the steel slag asphalt concrete reduces emissions by approximately 27.8%, resulting in about 274.9 tons of CO2eq per functional unit.

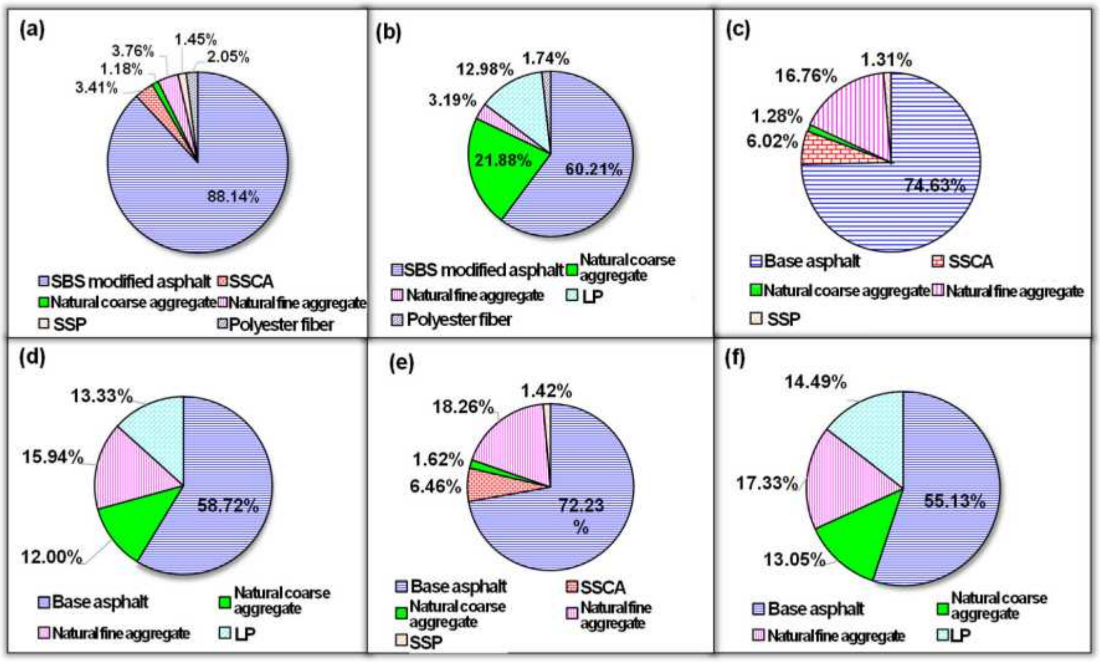


Figure 3 Carbon emission composition of the production of raw materials for asphalt concretes: (a) SS-SMA13; (b) NA-SMA13; (c) SS-AC20; (d) NA-AC20; (c) SS-AC25; (d) NA-AC25 (SS represents steel slag, and NA represents natural aggregate)

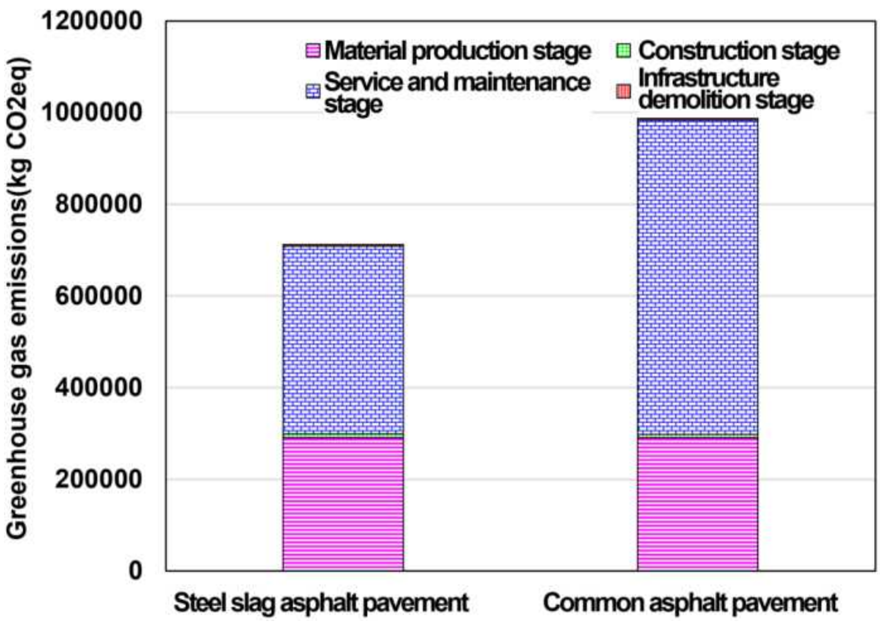


Figure 4 Carbon emission composition of asphalt pavement in their life cycle

Influence of compatibility between light oil and isocyanate compounds on rejuvenation properties and mechanisms of aged SBS modified bitumen

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Graphical abstract:

Figure 1 Graphical abstract

1 Objectives and Methodology

This study first subjected virgin SBS modified bitumen to short-term and long-term aging, then incorporated isocyanate reactive rejuvenators for rejuvenation. The rejuvenated bitumen was subjected to macroscopic and microscopic property tests to evaluate the rejuvenation effects and investigate the rejuvenation mechanisms. The objectives of this study are as follows: 1) Exploring whether the type of light oil affects the repair efficacy of isocyanate compounds.; 2) Analysing the compatibility between different light oil and isocyanate compounds; 3) Integrating macro-micro performance analysis recommends the optimal light oil/isocyanate compound ratio.

2 Major results and findings

Table 1 Major research results and findings Evaluation Dimension FCC Combination

Evaluation Dimension	FCC Combination Effect	AO Combination Effect	ESO Combination Effect
High-Temperature properties	Minimal impact on ASMB's high-temperature rutting resistance	Maintains stable high-temperature performance	Significantly weakens high-temperature rutting resistance

Medium and Low-Temperature properties	Limited rejuvenation effect	Medium rejuvenation effect	Optimal rejuvenation effect
SBS Repair Efficacy	Medium SBS crosslink density	Optimal SBS crosslink density	Poor SBS crosslink density; inhibits isocyanate repair of degraded SBS
Microscopic Mechanism	Worst dispersing capacity, unable to completely dissolve aggregated asphaltenes	Good dissolution for asphaltenes	High solubility in asphaltenes, replenishes lost light components in ASMB, acting as an excellent base asphalt rejuvenator
Component Compatibility	Weaker compatibility with HMDI than with IPDI	Excellent Compatibility with both HMDI and IPDI	Poor compatibility with both HMDI and IPDI
Optimal Dosage	10%	7%	4%

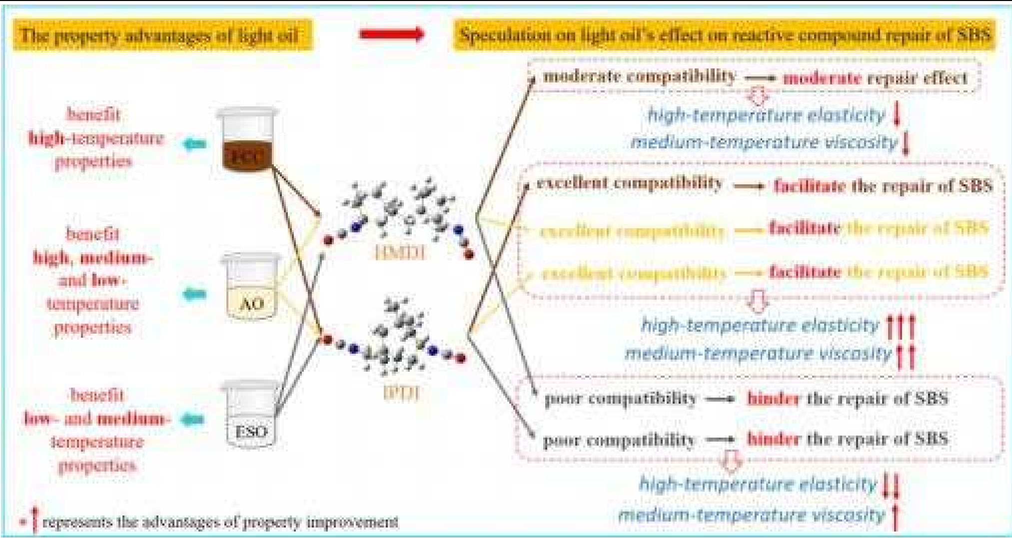


Figure 2 Influence of light oil on macroscopic effects of isocyanate compounds.

Parallel Session H3

Topic: Workshop of Interdisciplinary Research on Transportation Infrastructure

Chair: Xue Luo, Professor, Zhejiang University Cochair: Zhen Leng, Professor, The Hong Kong Polytechnic University

Introduction:

The development of modern transportation infrastructure increasingly relies on interdisciplinary collaboration, as the complexity of today's challenges extends beyond the boundaries of any single field. From low-carbon and high-performance materials to intelligent construction and climate-resilient design, innovations in transportation infrastructure demand the integration of materials science, chemistry, artificial intelligence, environmental engineering, and data science.

In particular, the emergence of advanced materials—such as bio-based binders, self-healing composites, and functional additives—offers new opportunities for enhancing durability, sustainability, and adaptability. These materials often exhibit heterogeneous, nonlinear, and multi-scale behavior, requiring novel experimental, analytical, and computational approaches to fully characterize and optimize their performance in real-world conditions.

At the same time, infrastructure systems are expected to operate in increasingly complex environments—subject to autonomous vehicle loading, extreme weather, and continuous monitoring through sensor networks. Addressing these challenges calls for cross-disciplinary methods that integrate material innovation, data-driven modeling, smart sensing, and adaptive design.

This session will highlight interdisciplinary research that advances the performance, resilience, and sustainability of transportation infrastructure. It will feature emerging methods, technologies, and concepts from across disciplines, with a focus on bridging the gap between fundamental research and practical engineering applications.

Speech:

Temperature Correction for Traffic Speed Deflectometer Measurements on Flexible Pavement Using ANN Models

Kairen Shen, Hao Wang, Francesco Canestrari, and Andrea Graziani, Department of Civil and Environmental Engineering, School of Engineering, Rutgers University

Research on Internal Structure Image Analysis of Asphalt Mixture and Method of Crack Resistance Performance Design

Jiaying Du, Yuan Zhang, School of Civil Engineering and Transportation, South China University of Technology

Field measurement and monitoring of oxygen concentration in asphalt pavements

Xingyu Chen, Yinghao Miao, and Yuhong Wang, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University

An Intelligent Approach for Identifying Void Clogging in Porous Asphalt

Pavements Using Tire-Pavement Interaction Noise

Ke Pei, Yuan Zhang, School of Civil Engineering and Transportation, South China University of Technology

Influence of Bio-oil Molecular Characteristics on Rheological Behavior and Interfacial Adhesion of Rejuvenated Asphalt: A 3D Rendering-assisted Quantitative Evaluation

Yefei Wang, Yuan Zhang, School of Civil Engineering and Transportation, South China University of Technology

Temperature Correction for Traffic Speed Deflectometer Measurements on Flexible Pavement Using ANN Models

Kairen Shen[1], Hao Wang[1], Francesco Canestrari[2], and Andrea Graziani[2]

1. Department of Civil and Environmental Engineering, School of Engineering, Rutgers University, New Brunswick, USA

2. Dipartimento di Ingegneria Civile, Edile, e Architettura (DICEA), Università Politecnica delle Marche, Ancona, Italy

1 Objectives of this research

This study aims to develop ANN models for temperature correction of TSD measurements. The semi-analytical finite element method (SAFEM) is used to simulate the TSD measurements and its accuracy is verified with field measurements. A synthetic database of TSD measurements is developed to account for various influencing factors including material properties, pavement structures, speeds, and temperatures. Further, this database is analyzed using ANN to develop the temperature correction method. Two correction models using deflection slopes as inputs demonstrate the study approach, while a model using deflections as inputs is validated with the measurements from the Italian test road.

2 Methodology and main research work

2.1 Methodology

The schematic for TSD simulation by SAFEM is shown in Figure 1. Firstly, the flexible pavement is treated as a layered system in SAFEM, of which asphalt layers are considered viscoelastic, and the other layers are assumed to be elastic. The constitutive relationships are selected as the generalized Maxwell model (GMM) and elastic model with Raleigh damping, respectively. The bottom and vertical boundaries are set as spring and dashpot, respectively, accounting for the subgrade supporting and soil stress-absorbing effects. The interface between adjacent layers is simulated as three-dimensional interface elements, of which shear stiffness is valued from directed shear tests with corresponding materials. Secondly, the tire pavement contact stress is estimated from empirical equations with specific tire types, applied loads, and inflation pressure. The contact stress of each rib is applied to the corresponding elements at the top boundary, where element meshing, only conducted in the cross-section, is optimized based on the loading positions and rib dimension. The discrete Fourier transform is operated by fitting the contact stress distribution along the longitudinal direction. The loading movement is achieved by the coordinate transformation of trigonometric functions in the Fourier series.

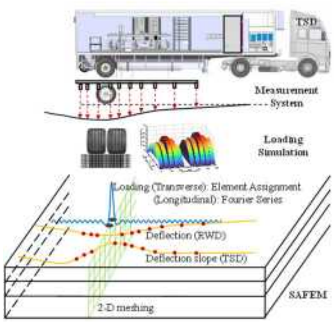


Figure 1 Schematic representation of TSDD testing in SAFEM.

2.2 Main research work

The TSD measurement database was developed using the SAFEM simulation. The flexible pavement for TSD simulation consists of three layers, an asphalt layer, a base, and subgrade. Ten different asphalt mixtures were selected from a previous LTPP study to represent the diversity of asphalt materials. The high-performance grade (PG) of asphalt binders varies from PG58 to PG64, while the low temperature grade is PG-28 to PG-22. The binders contain different modifiers or reclaimed asphalt contents. These mixtures are all dense graded mixes, of which air voids range from 3.7% to 7.5%. Therefore, these mixtures represent the diversities encountered in practical flexible pavements. The base modulus was selected as 300 MPa and 600 MPa to represent the weak and strong aggregate bases, respectively. The subgrade modulus was selected as 50 MPa and 100 MPa to consider different soil types and moisture conditions.

To consider pavement temperature variations, eight pairs of air and pavement surface temperatures in the morning or afternoon of different seasons were extracted from the LTPP database for generating temperature gradients based on the BELLS2 model. These temperatures are selected to cover a wide range of temperatures experienced in the field. Three speeds are simulated, including 36, 72, and 108 km/h, to see the relative effect of speed on TSD measurements as compared to temperature.

All the parameters for different scenarios are summarized in Table 1. A total of 5,760 cases were simulated using SAFEM to develop the synthetic database. Due to the efficiency of SAFEM, each case requires about two minutes on a computer workstation with a 16-core CPU that is highly efficient in terms of computation resources.

Table 1. Analysis parameters for TSD simulated by SAFEM

Parameters		Values
Air and surface Temperature (°C)	10:00	4&3, 10.1&12.4, 20.9&22, 30.3&33.2
	14:00	1.2&6, 9.24 &14, 19.8&30, 30.4&46
Asphalt concrete modulus		Viscoelastic modulus of 10 mixes
Asphalt thickness (cm)		10.2, 20.3, 30.5
Base thickness (cm)		30.5, 45.7
Base modulus (MPa)		300, 600
Subgrade modulus (MPa)		50, 100
TSD speed (km/h)		36, 72, 108
Total cases		8×10×3×2×2×2×3 = 5760

3 Major findings

The database was divided into the training dataset (80%) to generate the ANN model, while the remaining 20% data was used to test the model. The model verification results using the test dataset are shown in Figure 2, respectively, for the deflection slopes at all TSD sensor locations. The reference case has speed of 72 km/h and mid-depth temperature of 22°C. The prediction model demonstrates satisfactory accuracy for most measurements with R-square values over 0.95, except for the farthest sensor from the tire. The likely reason is that the measurement farthest from the tire is primarily influenced by base and subgrade layers, of which the temperature barely affects the modulus. The root mean square error (RMSE) of TCF between predicted and true values is within the range of 0.04-0.06.

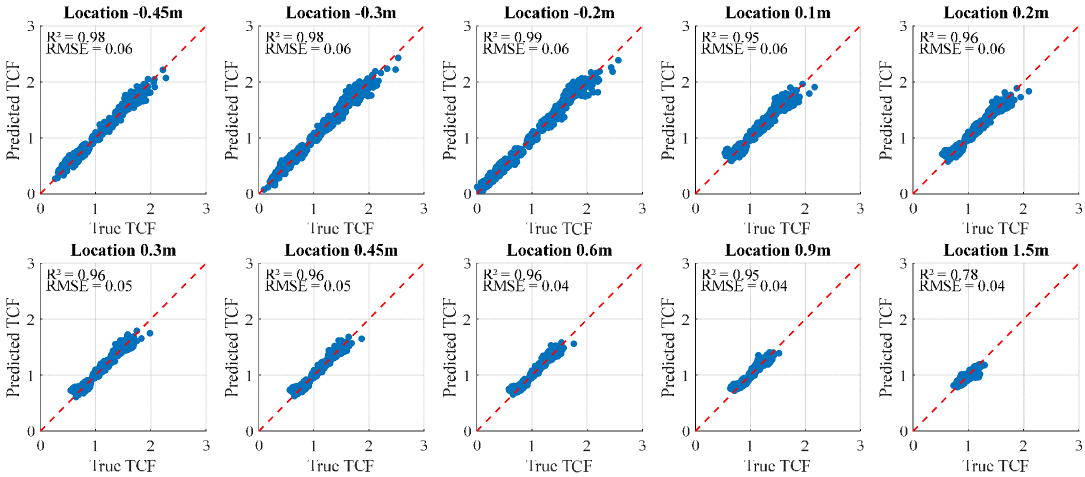
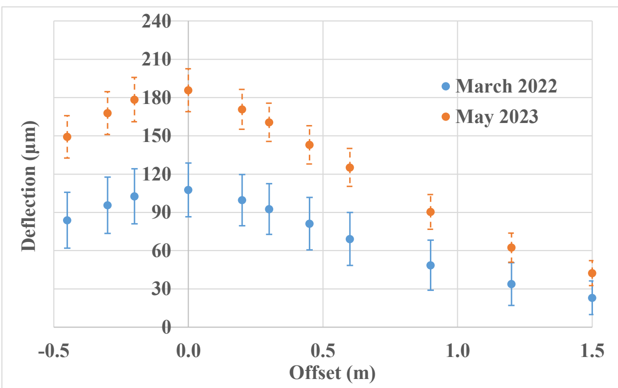
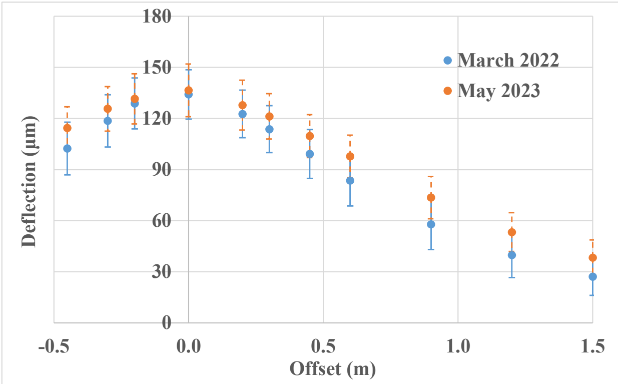


Figure 2. Prediction accuracy of ANN model for TCF using deflection slopes and mid-depth temperature as inputs (reference mid-depth temperature of 22°C)

Figure 3 shows the TSD deflections at different offsets, respectively, for the raw measurements and the converted data at the reference temperature and speed. The spatial variation of deflections from different measurement locations in the section was plotted using one standard deviation below and above the average value. As expected, the raw deflections measured in May 2023 are much greater than those in March 2022, especially at the sensor locations close to tire loading. The mid-depth temperature ranged from 11.3°C to 14.2°C in March 2022 and from 30.9°C to 31.1°C in May 2023 during TSD testing. After temperature correction, the deflections at the sensor locations close to tire loading are close to each other between March 2022 and May 2023. Although the deflections measured in May 2023 show slightly higher values, it is believed to be caused by pavement deterioration over one year. On the other hand, the discrepancy of deflections at the sensor locations far away from tire loading between two measurements keeps the same after temperature correction, which is mainly caused by base or subgrade modulus change due to moisture condition rather than temperature.



(a)



(b)

Figure 3 TSD deflections measured at two different times (a) raw measurements; (b) corrected data at reference temperature (22℃) and speed (72km/h).

4 Conclusion

This study analyzed temperature dependency of TSD-measured deflection slopes and developed ANN models to predict temperature correction factors (TCFs) considering various influencing factors (speed, asphalt layer thickness, mix type, base layer thickness, and base/subgrade modulus). The main conclusions can be drawn as follows:

1. SAFEM accurately simulates TSD testing, with simulation results for surface deflection and deflection slopes showing strong agreement with field measurements from two test roads.
2. Regression analysis of the developed database reveals that TCFs are significantly more sensitive to temperature than TSD speed. A 20 km/h increase in speed is approximately equivalent to 1°C decrease in the mid-depth temperature of asphalt layers.
3. ANN models are developed for temperature correction of TSD-measured deflection slopes at each offset using the inputs of raw measurements and mid- depth temperature of asphalt layer. The model accuracy is high with R-square values over 0.95 except the farthest sensor location at 1.5m.

   The ANN model for predicting TCFs of surface deflections was validated by TSD measurements in the field. The deflections at sensor locations close to the tire are corrected showing good agreements between different measurements without temperature effect.

This study demonstrated the effectiveness of data-driven models for temperature correction of TSD measurements on asphalt pavements. Future work should validate the developed temperature correction factors using TSD measurements at a wide range of pavement sections.

Research on Internal Structure Image Analysis of Asphalt Mixture and Method of Crack Resistance Performance Design

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Graphical abstract

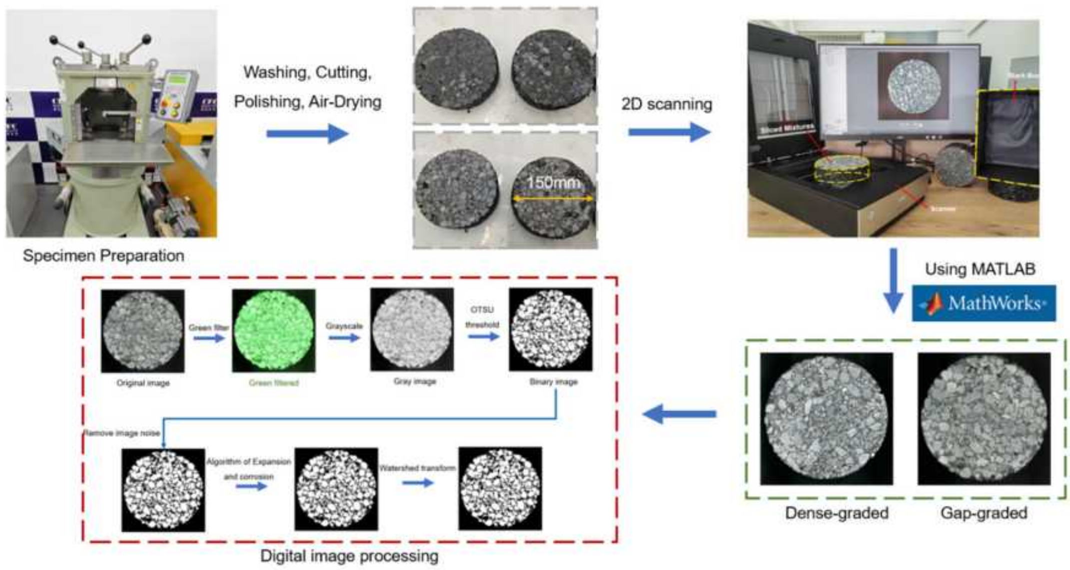

Figure 1 Cutting, scanning, and filtering steps for 2D image processing

1 Objectives and Methodology

Traditional asphalt mixture design methods—such as the Marshall method, Superpave system, and the CAVF approach—primarily rely on volumetric parameters, including Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and air voids (VV), to evaluate and control mixture performance. While these metrics, along with rutting and moisture susceptibility tests required in the Superpave protocol, help ensure minimum performance standards, they do not reflect the internal structure of the asphalt mixture. However, this internal structure plays a critical role in the development of pavement distresses and long-term durability.

Asphalt mixture is a typical multiphase composite material consisting of coarse aggregates, asphalt mortar, and air voids. Its internal structure refers to the spatial distribution and interactions among these components. Numerous studies have demonstrated that internal structural characteristics are closely correlated with mechanical behaviors such as rutting resistance and fatigue cracking. Although image-based techniques have been widely applied to evaluate aggregate distribution, the spatial characteristics and contribution of asphalt mortar remain under-investigated.

Asphalt mortar, composed of asphalt binder and fine aggregates (smaller than 1.18 mm), acts as a viscoelastic matrix that fills, bonds, and bridges coarse aggregates. It facilitates stress transfer and strain compatibility within the mixture. Research has shown that permanent deformation under high temperatures tends to concentrate in mortar-rich regions due to the mortar's relatively low stiffness. Moreover, crack initiation frequently occurs at mortar–aggregate interfaces, highlighting the critical role of mortar in crack resistance. Yet, limited attention has been paid to the distribution and mechanical implications of mortar-related internal structure—particularly with respect to mortar film thickness.

Mortar film thickness has increasingly been recognized as a key indicator of mixture durability and cracking resistance. In this study, a digital image analysis approach is developed to extract high-resolution 2D structural data from asphalt mixtures. This enables precise quantification of mortar film thickness distribution under varying gradation and asphalt–aggregate ratio conditions. The extracted internal structural parameters are then correlated with macroscopic cracking performance to establish a design framework that incorporates internal structure considerations. Mixtures with different gradation types and asphalt contents were prepared according to the Superpave design method. After cutting and polishing, the specimens were scanned using a high-resolution flatbed scanner to obtain 2D sectional images. To enhance image clarity, the green (G) channel was selectively amplified to improve phase contrast. A hybrid grayscale–mask background removal algorithm was then applied to correct lighting inconsistencies and eliminate background noise. Image segmentation was performed using an enhanced dual-threshold method based on OTSU's algorithm. The accuracy of segmentation was validated by comparing pixel-based component areas and gradation curves with actual mixture data. Processing parameters were iteratively adjusted until the relative error was within ±5%. Mortar film thickness was measured by identifying the shortest distance from coarse aggregate boundaries to neighboring particles along the normal direction within a defined search radius. The extracted thickness values were statistically analyzed and fitted using chi-square distribution models to derive key parameters such as mean, standard deviation, skewness, and kurtosis.

These internal structure metrics were further analyzed for their relationship with conventional volumetric parameters. Digital Image Correlation (DIC) was employed to obtain full-field strain maps under mechanical loading. Strain localization in mortar regions was isolated to investigate their role in deformation and damage evolution. By linking mortar film thickness characteristics to cracking performance indicators, a predictive model was developed, offering an internal-structure-based approach to crack-resistant asphalt mixture design.

2 Major results and findings

The optimal enhancement factor for the G-channel can be determined by modeling its relationship with the OTSU threshold gap, maximizing grayscale contrast between phases and improving multiphase segmentation accuracy.

A custom threshold–mask background removal method effectively eliminates background noise while preserving void pixels, addressing the limitations of direct thresholding and improving segmentation reliability.

Mortar film thickness distribution is significantly affected by gradation type. AC mixtures exhibit more concentrated distributions with higher peak values, indicating a more uniform and stable mortar structure. In contrast, SMA mixtures show broader distributions with lower dominant thickness values, suggesting potential thin-film weaknesses. Lower standard deviation and narrower distribution curves are associated with better structural consistency and crack resistance. These mortar film thickness parameters serve as reliable indicators of internal structural quality and offer valuable guidance for performance-based mixture design.

Field measurement and monitoring of oxygen concentration in asphalt pavements

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Abstract

1 Objectives and Methodology

Oxidative aging of asphalt binders poses a significant threat to the long-term performance of asphalt pavements. The progression of oxidation within asphalt pavements is influenced by a variety of factors, including the properties of the asphalt binder, the gradation of each pavement layer, the overall pavement structure, and environmental conditions. Among these, temperature and oxygen are two key environmental factors that govern the aging rate of asphalt binders, as dictated by the kinetics of oxidation. While extensive research has been conducted on the temperature distribution within asphalt pavements, the distribution of oxygen has not been thoroughly explored. Traditional empirical models, such as the global aging model employed in the MEPDG method, typically assume that aging decreases with pavement depth, reaching zero at a certain point [1]. However, this assumption fails to account for field observations where aging initially decreases with depth and then increases again, resulting in an "aging turning point" phenomenon [2-3]. Considering that temperature has been approved to decrease with pavement depth, it is highly possible that the arc-shape distribution of aging in pavements is generated by oxygen. Therefore, a comprehensive understanding of oxygen distribution within asphalt pavements is essential for advancing research on pavement aging.

To investigate oxygen concentration within asphalt pavements, a trial section measuring 4 m × 6 m × 0.46 m was constructed at the National Center for Materials Service Safety in Beijing, which was shown in Fig. 1. The trial asphalt pavement section consists of several layers: 18 cm of soil, 18 cm of ATB-25, 6 cm of AC-20, and 4 cm of SMA-13. The construction of the trial section followed the designed structure, starting from the soil base and progressing to the wearing course. During the compaction process of each layer, oxygen collection systems and protective tubes were inserted into the trial section through the positioning slots. Subsequently, oxygen sensors were connected to the oxygen collection systems and data acquisition system for field monitoring of oxygen concentration.

Fig. 1 A trial section of asphalt pavement for oxygen measurement and monitoring

2 Major results and findings

The 8-months monitoring results of oxygen concentration in different layers were shown in Figure 2. Based on the dynamic monitoring data of oxygen concentration obtained from the full-scale test section, preliminary analysis reveals that the oxygen concentration exhibits a significant non-monotonic distribution along the depth direction. Its "first decreases and then increases" trend is highly spatially coupled with the aging distribution curve discussed in the last section. This discovery is the first in the industry to experimentally confirm the non-monotonic distribution characteristics of deep oxygen fields, providing direct evidence for explaining the phenomenon of the 'aging turning point'.

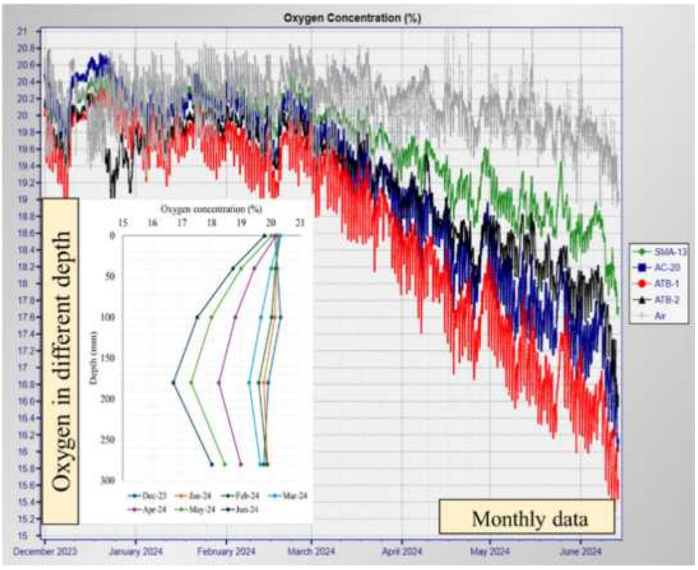

Fig. 2 8-months monitoring results of oxygen concentrations in asphalt pavements

An Intelligent Approach for Identifying Void Clogging in Porous Asphalt Pavements Using Tire-Pavement Interaction Noise

Ke Pei[1], Yuan Zhang[1]

[1] School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510641, China, kepei_job@163.com

Graphical Abstract

Figure 1 Graphical Abstract

1 Objectives and Methodology

This study aims to investigate how void clogging develops in porous asphalt pavements during long-term service. It focuses on identifying the key factors that cause performance decline. Based on this understanding, it proposes an intelligent method that uses acoustic signals to detect the degree of clogging. This method improves the accuracy of clogging evaluation. As a result, it helps to support more efficient maintenance and extend the service life of porous asphalt pavements.

The specific objectives are as follows:

(1) To clarify the evolution patterns of drainage performance and void clogging under different service years and lane positions.

(2) To reveal how void clogging affects acoustic performance and to explore the coupled degradation of drainage and noise reduction functions.

(3) To develop a multi-dimensional acoustic signal recognition model based on a Deep Residual Fully Connected Network (DRFCN) for automated clogging classification.

(4) To validate the model's accuracy through on-site pore-cleaning trials and to propose recommendations for optimal maintenance timing.

To achieve these objectives, a multi-scale and multi-method research framework is adopted. Field sampling and permeability testing, combined with statistical analysis, are employed to investigate the mechanisms of clogging evolution. Laboratory clogging simulations and onboard sound intensity (OBSI) measurements are carried out to evaluate the impact of clogging on acoustic properties. Time-domain, frequency-domain, and Mel-frequency cepstral coefficient (MFCC) features are extracted from acoustic signals and used as input parameters for the DRFCN based recognition model. Finally, typical test sections are selected for pore-cleaning validation, establishing a closed loop research system that integrates mechanism investigation, model development, and practical application.

2 Major Results and Findings

This study systematically developed statistical models for void clogging evolution based on long-term monitoring data from porous asphalt pavements, quantitatively characterizing drainage performance degradation across different service years and lane positions, thus providing a theoretical foundation for precision maintenance.

A significant correlation between void clogging and acoustic characteristic parameters was established, providing a robust data-driven and mechanistic basis for acoustic signal-based clogging detection and promoting the advancement of non-destructive evaluation techniques.

Multi-dimensional acoustic features were innovatively extracted from tire–pavement contact noise signals, and signal quality was effectively enhanced through band-pass filtering and wavelet threshold denoising, ensuring accurate identification of clogging conditions.

A high-accuracy clogging level recognition model was developed using a Deep Residual Fully Connected Network (DRFCN), achieving over 90% classification accuracy and significantly advancing the automation and intelligence of porous asphalt pavement clogging detection technologies.

Influence of Bio-oil Molecular Characteristics on Rheological Behavior and Interfacial Adhesion of Rejuvenated Asphalt: A 3D Rendering-assisted Quantitative Evaluation

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Graphical Abstract

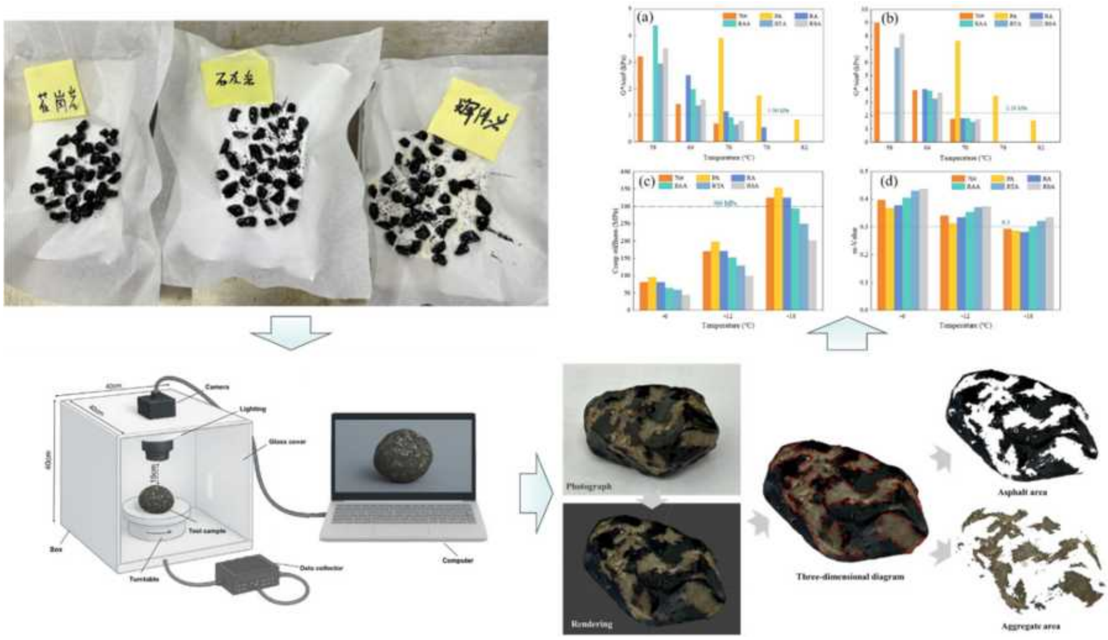


Figure 2 Graphical Abstract

1 Objectives and Methodology

The large-scale utilization of Recycled Asphalt Pavement (RAP) has become a key strategy for enhancing circular economy principles in road engineering, driven by increasing road maintenance demands and sustainability goals. Incorporating RAP—now common practice in the United States, China, and Europe—significantly reduces virgin material consumption, construction costs, and carbon emissions. However, the aged asphalt binder within RAP undergoes substantial physicochemical deterioration during service life, including loss of active polar components, increased stiffness, and weakened adhesion to aggregates. These changes impair the mechanical performance and long-term durability of recycled asphalt mixtures.

To restore the functionality of aged asphalt and ensure the performance of recycled mixtures, the addition of rejuvenators has emerged as a key strategy. Rejuvenators are functional additives specifically formulated to restore the original rheological and interfacial properties of aged asphalt by modifying its molecular architecture and component distribution. According to their sources, rejuvenators are generally classified into two main categories: petroleum-derived aromatic oils and bio-based formulations . Aromatic oil rejuvenators typically reduce the viscosity of aged asphalt by diluting large molecular structures; however, their limited polarity restricts their ability to improve low-temperature flexibility and enhance adhesion at the asphalt–aggregate interface. In contrast, bio-based rejuvenators, such as soybean oil, tall oil, and waste cooking oil, contain abundant small- and medium-sized fatty acid esters with both flexible backbones and polar functional groups. These molecules not only facilitate the depolymerization of aged asphalt chains and enhance low-temperature flexibility, but also strengthen the interfacial bonding between asphalt and mineral aggregates through hydrogen bonding or Lewis acid–base interactions.

Currently, the evaluation of interfacial adhesion remains largely dependent on conventional boiling tests or two-dimensional image-based identification methods, which are often subjective, poorly reproducible, and limited in spatial resolution. As a result, these approaches fail to fully capture the three-dimensional (3D) morphology of asphalt residue on aggregates, hindering accurate quantification and deeper understanding of polarity-driven adhesion mechanisms. Moreover, a lack of systematic experimental methods for linking rejuvenator molecular structure, macro-scale mechanical behavior, and micro-scale interfacial performance limits further progress in rational rejuvenator design.

To address these limitations, this study proposed a novel evaluation method that combined ultrasonic stripping tests with pixel-based 3D image reconstruction and rendering. Multi-angle imaging was used to generate three-dimensional surface models of stripped aggregates, enabling the visualization and quantification of residual asphalt films. The image data was then integrated with contact angle and surface energy to characterize asphalt wetting behavior after rejuvenator treatment. By correlating 3D rendering outcomes with micro-scale physicochemical parameters, a closed-loop evaluation system was established that links image-based observation, quantitative metrics, and interfacial behavior.

Following this framework, three representative rejuvenated asphalt systems were formulated. Their performance was systematically assessed through gel permeation chromatography (GPC), dynamic shear rheology (DSR), and bending beam rheological (BBR). These tests revealed how the molecular structure of rejuvenators affected viscoelastic recovery and flexibility. The proposed 3D image-based method, supported by contact angle and surface energy measurements, offered a more comprehensive evaluation of anti-stripping performance. Overall, this study presented an innovative multi-scale assessment approach that bridged macro-level properties, micro-scale mechanisms, and visual quantification, while contributing a methodological foundation for the rational design of high-performance, environmentally sustainable rejuvenators.

2 Major results and findings

This study aims to evaluate the multi-scale performance recovery of aged asphalt using bio-based rejuvenators. To achieve this, molecular characteristics, rheological behavior, interfacial adhesion, and microstructure were tested through GPC, DSR, BBR, contact angle, surface energy, and Pixel 3D rendering. Three rejuvenated asphalt systems and three typical aggregates (limestone, granite, and diabase) were used for performance evaluation. A novel 3D-assisted method was developed to quantify interfacial adhesion.

The relationship between molecular structure, rheological performance, and interfacial behavior was discussed. This study concludes the following findings:

RSA (SO-rejuvenated asphalt) demonstrated the highest stripping resistance across all three aggregate systems (limestone, granite, and diabase) after 120 min of ultrasonic stripping, with an average retained asphalt ratio of 73.25%, significantly outperforming RTA (TO-rejuvenated asphalt) and RAA (AO-rejuvenated asphalt). This is attributed to the polar functional groups in RSA forming stable chemical adsorption at the interface.

The proposed Pixel 3D reconstruction method effectively quantified the residual asphalt coverage ratio, offering spatially resolved insights into stripping behavior. Its results showed a strong correlation with contact angle measurements and surface energy analysis, proving the method's accuracy, sensitivity, and practical feasibility.

GPC analysis confirmed that RSA reduced the LMS (large molecular size) fraction by 22.11%, accompanied by a 7.37% increase in MMS (medium molecular size) content, reflecting substantial molecular depolymerization and colloidal structure reconstruction.

Rheological results revealed that RSA lowered $G^*/\sin\delta$ by 16.25% at high temperatures and improved the m-value by 22.82% at low temperatures, along with reduced S-values. This demonstrates enhanced rutting resistance at high temperatures and improved flexibility and stress relaxation at low temperatures.

Surface energy analysis showed that RSA achieved the highest polar interaction energy (= 1.73 mJ/m^2) and positive polarity (= 1.97 mJ/m^2), significantly higher than RTA and RAA, contributing to superior interfacial adhesion and moisture stability.

Future work should focus on designing multifunctional rejuvenators that integrate flexibility modulation and interfacial polarity, combined with life-cycle assessment and field validation, to enhance low-temperature crack resistance, moisture durability, and sustainability of recycled asphalt materials.

Parallel Session H4

Topic: Multiscale Mechanics and Data-driven Modelling for Climate Resilient Road Infrastructure and Materials

Chair: Yangming Gao, Senior Lecturer, Liverpool John Moores University Cochair: Fan Gu, Professor, Changsha University of Science & Technology; Xueyan Liu, Associate Professor, Delft University of Technology

Introduction:

Road infrastructure systems are facing serious challenges due to climate change. Road material deterioration and structural distresses are increasing in frequency and severity under extreme weather and natural hazards. Recent research has been focused on the interactions between extreme events and road infrastructure systems, transforming road networks to be resilient to climate change. As the kernel of performance prediction, multiscale mechanics and data driven modeling lay down a solid foundation for material selection, design and evaluation of resilient road infrastructure systems. Innovative research provides insight into understanding, assessment, optimization, and management of the climate resilience and sustainability of road structures and materials at multiple scales. The topics of interest include but are not limited to:

a. Characterization of extreme events caused by climate change
b. Natural hazards' interactions with road infrastructure
c. Impact of coastal hazards on port pavements and coastal roads
d. Multiscale, multiphase, and multiphysics resilience modeling of paving materials
e. Spatial data/AI for road resilience assessment and optimization
f. Nature-based solutions to enhance road infrastructure resilience
g. Climate-adaptive road infrastructure management strategies and their sustainability

Speech:

Keynote Speech Porous Road Structure for Urban Flooding Mitigation

Yuhong Wang, Professor, The Hong Kong Polytechnic University

Impacts of Climate Change on Asphalt Pavement Infrastructure

Shu Yang, Associate Professor, Hunan University

Urban road flood resilience and management

Yaning Qiao, Associate Professor, China University of Mining and Technology

Preparation of a high stability-viscosity-elasticity composite modified asphalt with bio-devulcanized rubber powder

Derun Zhang; Jinbiao Tang; Shangxian Xie; Ruben Paul Borg; Odette Lewis, School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology

Effect of coordination number of particle contact force on rutting resistance of asphalt mixture under high temperature conditions

Dongyu Niu, Associate Professor, Chang'an University

Keynote Speech Porous Road Structure for Urban Flooding Mitigation

Yuhong Wang, Professor, The Hong Kong Polytechnic University

Abstract:

Urban flooding is a persistent problem in many cities, often made worse by roads and pavements that don't let water drain away quickly. This study developed a new road structure designed to tackle this issue—not by using porous materials, but by incorporating holes and textured surfaces directly into the pavement. These features guide rainwater off the road and into drainage systems more efficiently, helping to prevent water from pooling and causing floods. This presentation introduces the design process, explains how the placement of holes and the choice of surface textures improve drainage, and shares results from tests and real-world trials. The presentation also covers practical aspects like maintenance, durability, and costs, showing how this porous road structure can fit into existing urban infrastructure. By rethinking how we build roads, cities can better manage stormwater and reduce the impact of heavy rains. The results indicate that this design can be adopted more widely to support safer, more resilient urban environments.

Impacts of Climate Change on Asphalt Pavement Infrastructure

Shu Yang, Associate Professor, Hunan University

Abstract:

Climate change is impacting on pavement infrastructure in China. To eliminate the issues of asphalt freeway pavement caused by climate change, this study evaluated the temperature change in China from 2020 to 2059. The related pavement issues include rutting, fatigue life, and thermal crack caused by climate change are assessed based on the prediction models incorporated with the predicted future climate. The potential future distresses were analyzed, quantified, and cataloged, then the effectiveness of optional adaptation measures included adjustment of structure thickness, dynamic modulus, and creep stiffness were analyzed. Finally, a method to select and quantify the adaptation measures was developed based on the effective analysis of adaptation measures. The major findings of this study are listed below: (1) Temperature rise is the general trend, rutting and fatigue issue is typical issue caused by climate change. (2) Extreme low temperature issues would occur more severely for some areas in future, up to 35% of pavements would have more severe thermal crack issues caused by climate change in 2050s. (3) Six quantified adaptation measures were suggested to solve these two types of issues caused by climate change.

Urban road flood resilience and management

Yaning Qiao, Associate Professor, China University of Mining and Technology

Abstract:

Climate change is intensifying extreme rainfall, challenging urban flood resilience, particularly in road networks. This study examines key resilience factors, including external drivers (e.g., extreme precipitation) and internal determinants like soil infiltration capacity, drainage efficiency, and terrain. Results show municipal drainage systems are most critical for mitigating waterlogging, outperforming surface permeability and soil retention. Disaster risk reduction must consider infrastructure interdependencies among roads, drainage, and underground spaces. The study concludes that combining drainage upgrades, permeable surfaces, and digital tools offers the best path to climate-resilient cities. Policymakers should prioritize cost-effective infrastructure planning and management to achieve flood resilience and sustainable development.

Preparation of a high stability-viscosity-elasticity composite modified asphalt with bio-devulcanized rubber powder

Derun Zhang[1]; Jinbiao Tang[1]; Shangxian Xie[2]; Ruben Paul Borg[3]; Odette Lewis[3]

[1] School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China, derunzhang@hust.edu.cn

[2] College of Life Science and Technology, Huazhong University of Science and Technology, Wuhan, 430074, China, shangxian_xie@hust.edu.cn

[3] Faculty for the Built Environment, University of Malta, MSD 2080, Msida Malta, ruben.p.borg@um.edu.mt

Graphical abstract

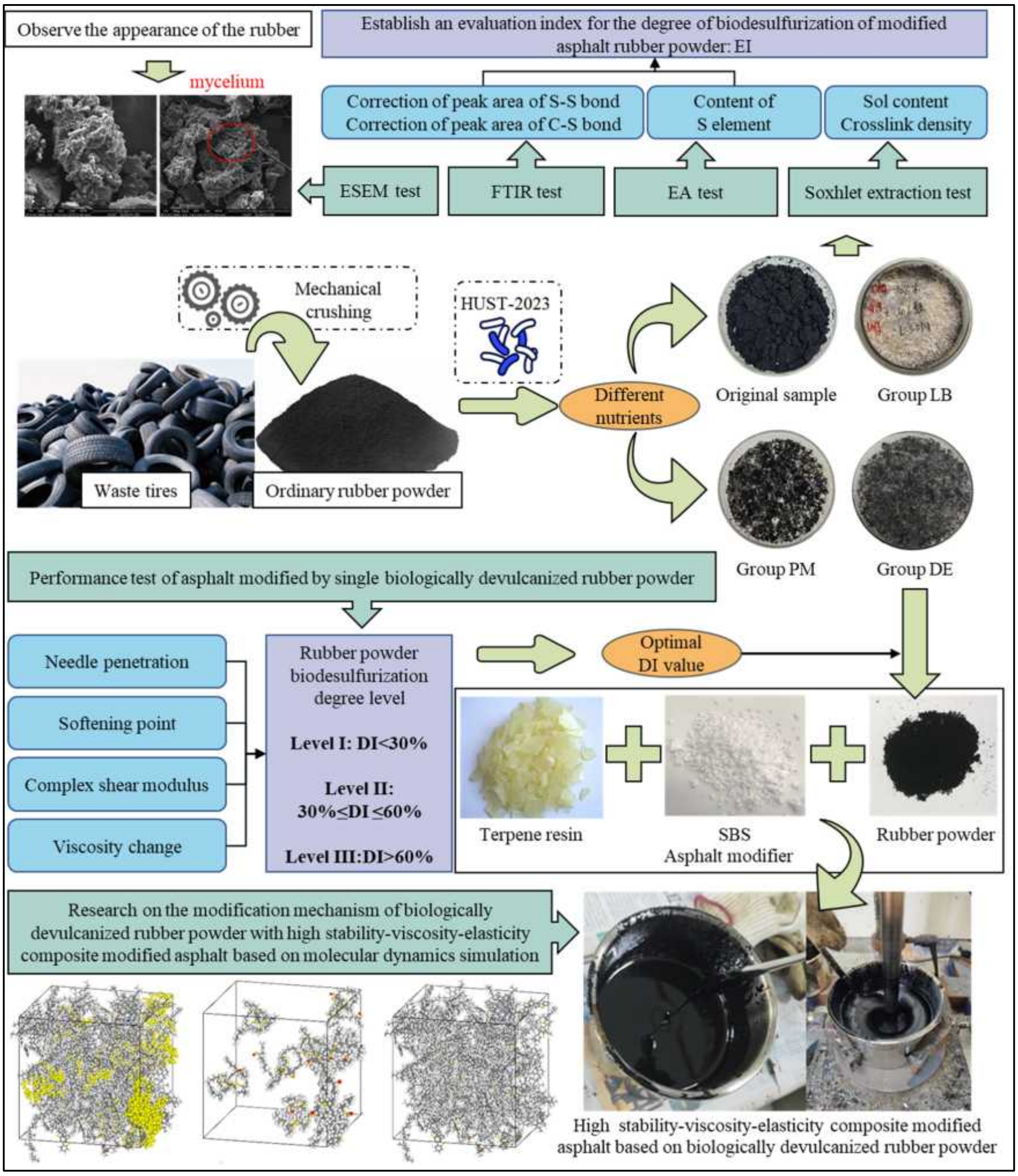
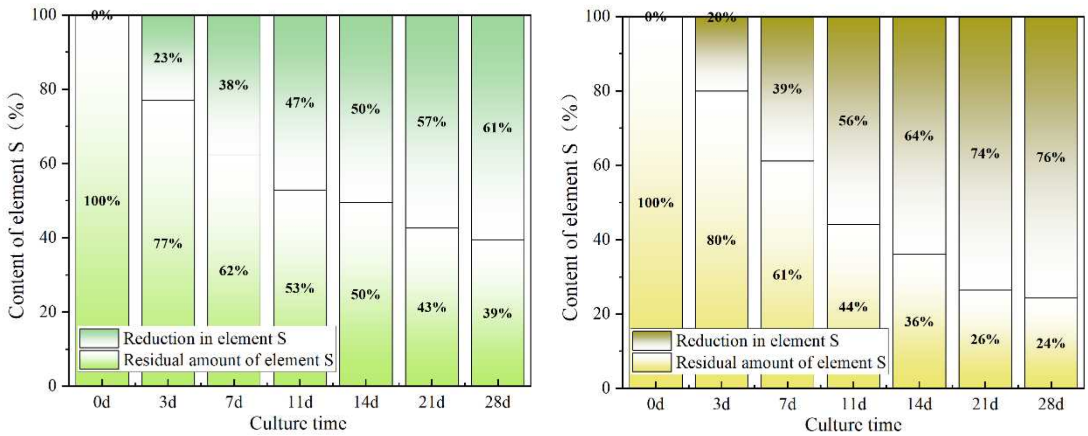


Figure 1 Graphical abstract

1 Objectives and Methodology

In order to effectively alleviate the performance drawbacks of rubber/SBS high viscoelastic composite modified asphalt, devulcanized rubber is increasingly used as a substitute for conventional rubber in asphalt modification. Biological devulcanization is characterized by environmental friendliness and precise targeting, but there is still a lack of bio-desulfurization microorganism with high activity and facile cultivation. Therefore, this study inoculated a novel microorganism HUST-2023 onto waste tire rubber powder to produce biologically devulcanized rubber powder. The microscopic devulcanization mechanism was investigated, the degree of devulcanization was quantitatively evaluated, and the optimal bio-desulfurization conditions were identified. Subsequently, a high viscosity-elasticity composite-modified asphalt with excellent storage stability, based on the biologically devulcanized rubber powder was synthesized. The nano-scale compatibility improvement mechanism was finally explored through the molecular dynamics simulation.

2 Major results and findings



（a）Group PM （b）Group DE

Figure 2 Changes in the sulfur element content of bio-devulcanized rubber powder

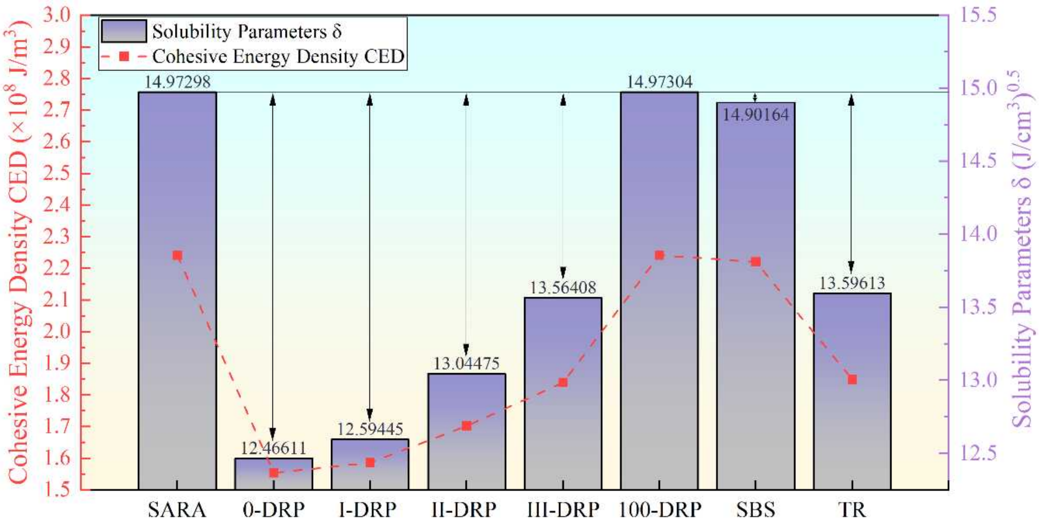


Figure 3 Solubility parameters of rubber molecules of different desulfurization grades and four components of SBS, TR and asphalt

Effect of coordination number of particle contact force on rutting resistance of asphalt mixture under high temperature conditions

Dongyu Niu, Associate Professor, Chang’an University

Abstract:

基于颗粒堆积理论与细观接触力学，提出了表征主骨架结构细观接触特征的粗集料接触配位参数（Cnpcf）。结合图像处理技术，将 Cnpcf 与骨料接触区数（CZ）进行了定量相关性分析，验证了 Cnpcf 用于表征细观骨架结构额可行性。当主骨架结构粗集料含量为 57%，干涉集料的比例为 7.5%时，相应的混合料具有良好的抗车辙表现。利用 Mann-Whitney U 检验对车辙试验前后样品的颗粒接触分布特性进行分析，证明了 CNpcf 对沥青混合料优化设计的有效性。该研究结果为细观结构尺度优化沥青混合料性能提供了新思路。

Parallel Session H4 Summary:

The session discussion focused on Climate Resilient Road Infrastructure and Materials. The following key challenges were identified.

1 Conventional road design standards, which are largely based on historical climate data, may be inadequate under projected increases in flooding, extreme heat, and freeze-thaw events, thereby necessitating the integration of forward-looking climate projections into design methodologies.

2 Limitations in current construction materials were discussed, with particular emphasis on the susceptibility of conventional asphalt concrete to climate-induced deterioration, and the need for further research into alternative materials such as polymer-modified binders, geopolymers, and recycled composites, while also addressing questions of cost-effectiveness and scalability.

3 The absence of comprehensive life-cycle assessment frameworks that account for long-term climate stressors, adaptation costs, and maintenance requirements was highlighted, which hampers accurate evaluation of resilience benefits.

4 Institutional and financial challenges were recognized, including fragmented governance structures, restricted funding availability, and the limited incorporation of resilience metrics into procurement and investment practices, all of which constrain proactive adaptation measures.

5 The importance of interdisciplinary collaboration was emphasized, particularly the integration of material science, geotechnical engineering, hydrology, and policy research, in order to develop effective and implementable solutions. Collectively, these challenges underscore the complexity of advancing climate resilience in road infrastructure and the need for both technical innovation and supportive policy frameworks.

Parallel Session I3

Topic: Cutting-Edge AI Techniques for the Future of Civil Engineering

Chair: Fangyu Liu, Professor, Tongji University
Cochair: Xiaojun Li, Professor, Tongji University; Zhoujing Ye, Associate Professor, University of Science and Technology Beijing
Speech:
Infrared Thermography and Deep Learning for Pavement Distress Detection
Fangyu Liu, Professor, Tongji University
Machine Learning and Deep Reinforcement Learning for Asphalt Concrete Mix Design
Jian Liu, Lecturer, University of Georgia
Exploration and Practice of AI Empowering the Construction Industry
Ruifeng Luo, East China Architectural Design & Research Institute Co., Ltd., Huajian Group
Geological Digital Twin of Tunnel Construction Based on Multi-Source Information Fusion
Huaiyuan Sun, Phd student, Tongji University
Research on Trajectory Optimization of Intelligent Arch Trolley Based on Particle Swarm Optimization
Ruijia Li, Phd student, Tongji University

Parallel Session I4

Topic: Round-Table Forum (Future Underground Space: Resilience, Intelligence and Sustainability)

Chair: Qing Chen, Professor, Tongji University
Cochair: Yafei Qiao, Associate Professor, Tongji University

Guests:
Wenqi Ding, Professor, Tongji University
Ruifeng Luo, Engineer, East China Architectural Design & Research Institute Co., Ltd., China State Construction Engineering Corporation

Parallel Session J3

Topic: Sustainable Solutions for Road Infrastructure Resilience

Chair: Mingliang Li, Professor, Research Institute of Highway, Ministry of Tra nsport
Co-chair: Fang Wang, Professor, Ningxia University
Speech:
Investigation on Long-Term Performance and Application of Hot In-Place for Porous Asphalt Pavement
Mingliang Li, Professor, Research Institute of Highway, Ministry of Transport
Study on the stability of emulsified asphalt with high asphalt content and optimisation of its influencing factors
Lingyun Kong, Professor, Chongqing Jiaotong University
Assessment and Early Warning of Driving Safety Risks on Expressway in Sandstrom
Fang Wang, Professor, Ningxia University
Research on Runway Life Based on the Size Effect of Slabs
Chunxiang Qi, Associate Professor, Civil Aviation University of China
Activation Energy Balanced Design Approach for Recycled Asphalt Binder Blends
Jingxian Xu[1], Xue Luo[1], and Dong Liu[2], College of Civil Engineering and Architecture, Zhejiang University

Investigation on Long-Term Performance and Application of Hot In-Place for Porous Asphalt Pavement

Mingliang Li[1], Jun Li[1], and Dongcang Sun[1]
[1] Key Laboratory of Transport Industry of Road Structure and Material, Research Institute of Highway Ministry of Transport, Xitucheng Road No. 8, Beijing 100088, China, ml.li@rioh.cn

Graphical abstract

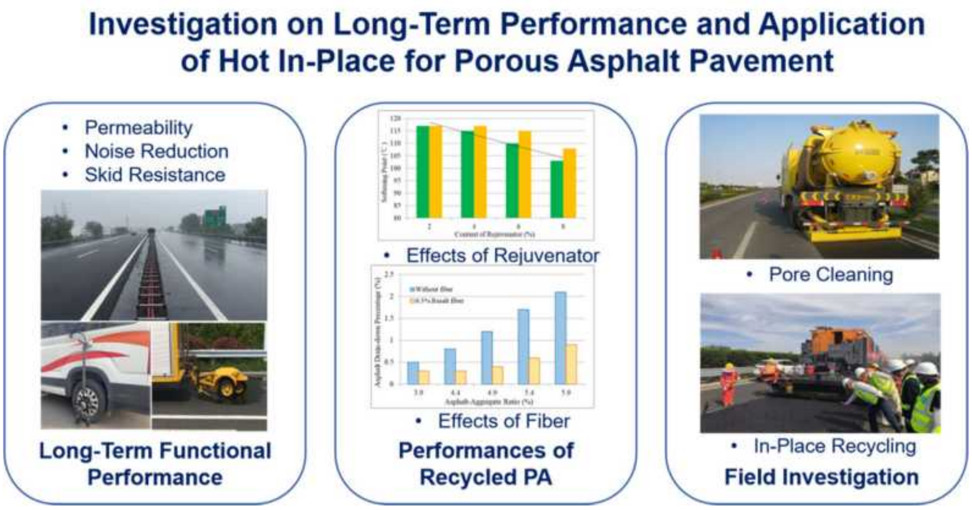


Figure 1 Graphical abstract

1 Objectives and Methodology

1.1 Objectives

The research aims to investigate the long-term functional performance of porous asphalt (PA) pavements in China, with a focus on drainage, skid resistance, and noise reduction. It analyzes the properties of aged PA mixtures and evaluates the effects of rejuvenators and fibers on recycled mixtures. The feasibility and effectiveness of Hot In-Place Recycling (HIR) in restoring drainage capacity and mechanical performance are also investigated.

1.2 Methodology

(1) Field performance monitoring: The Huai'an–Xuzhou Expressway (G2513) with 146.6 km of two-layer porous asphalt pavement was selected for long-term monitoring of permeability, skid resistance, texture, and tire–road noise over up to 9 years of service.

(2) Material properties: Aged asphalt was extracted and tested for penetration, softening point, ductility, and viscosity. Two rejuvenators, namely plant-based RR18 and petroleum-based PR-01, were compared, along with basalt fiber effects and varying proportions of new mixture.

(3) Hot In-Place Recycling (HIR) trial: HIR was implemented, including heating, mixing, adding new mixture, repaving, and compaction. Pore cleaning efficiency, void structure restoration, mixture properties, and post-recycling permeability were

evaluated.

2 Major results and findings

2.1 Long-term functional performance

Monitoring on the Huai'an－Xuzhou Expressway showed a steady decline in permeability, with clogging first in wheel tracks and later in emergency lanes. Clogging materials were mainly fine particles with high organic content. Skid resistance decreased 2－3 SFC/year, and microtexture was largely lost after five years. Tire－road noise increased over time, with heavy lanes consistently noisier.

2.2 Material properties of aged and recycled mixtures

Aged asphalt showed severe hardening, while rejuvenators—especially plant-based RR18—improved penetration and reduced viscosity. Adding new mixture increased resistance to raveling, water damage, and low-temperature cracking, and basalt fiber reduced drain-down loss from 1.2% to 0.4%.

2.3 Hot In-Place Recycling (HIR) application results

HIR restored void connectivity and improved permeability at most sites, with nine of ten points exceeding the design value. All mechanical properties met design requirements, confirming HIR as an effective method for porous asphalt pavement maintenance.

Table.1 Test results of performances of recycled porous asphalt mixture

Performance Indicators	Test Results	Design Target
Voids content(%)	17.4	≥16
Marshall stability(kN)	16.2	≥5
Drain-down percentage(%)	0.073	≤0.8
Standard raveling loss(%)	14.7	≤15
Immersion raveling loss(%)	18.0	≤20
Dynamic stability(time/mm)	8796	≥5000
Residual Mashall stability percentage(%)	87.9	≥85
Residual Freeze-thaw split tensile strength ratio(%)	87.5	≥80

Study on the stability of emulsified asphalt with high asphalt content and optimisation of its influencing factors

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* Corresponding author: Lingyun Kong, Email: konglingyun@cqjtu.edu.cn.

Graphical abstract.

Figure 1 Graphical abstract

High-asphalt-content emulsified asphalt (HIACE) demonstrates tremendous application potential in heavy-traffic highway construction due to its superior bonding strength, durability, and low-temperature resistance. However, while previous studies have explored the relationship between preparation methods and HIACE performance, the stability control mechanisms remain unclear, and research linking microstructural evolution with stability performance through image processing techniques is still limited. Traditional emulsified asphalt is typically prepared using colloid mills, with an asphalt content of 60-70% and a broad droplet size distribution (5-50μm). When the asphalt content exceeds 70%, technical challenges such as viscosity constraints arise, which affect aggregate adhesion and long-term storage stability. As a high internal phase emulsion (HIPE), HIACE contains a dispersed asphalt phase occupying more than 74% of the total volume, and preparation through high internal phase ratio methods enables precise control of emulsion microstructure. This study employs a one-step method to prepare and utilises fluorescence microscopy to quantify droplet size dynamics and their impact on stability mechanisms. Key preparation parameters affecting HIACE stability were systematically investigated, including stirring speed, mixing time, asphalt content, and emulsifier concentration. Using orthogonal experimental design, the study evaluated high-temperature demulsification resistance, room-temperature delamination resistance, and freeze-thaw durability through fluorescence microscopy observation, dynamic shear rheology scanning, dispersibility testing, and freeze-thaw cycle experiments.

An integrated image processing method based on random forest algorithms and principal component analysis (PCA) was developed to quantify droplet size dynamics and microstructural evolution effectively. Comparative analysis of image processing techniques revealed that traditional threshold segmentation methods have limitations when processing complex emulsion structures, while random forest algorithms significantly improve droplet boundary detection accuracy through multi-feature classification (colour, texture, spatial relationships). PCA analysis results showed that principal component 1 (PC1) explained 94.8% of the variance, establishing droplet diameter as the optimal characteristic value for representing HIACE microscopic images.

The research findings demonstrate: (1) As stirring speed increased from 500 rpm to 1500 rpm, average droplet size decreased from 10.43μm to 4.57μm. Asphalt content had the most significant impact on droplet size, with droplet size decreasing significantly from 10.64μm to 3.00μm when asphalt content increased from 75% to 89%. Polar analysis revealed the importance ranking of influencing factors as: asphalt content > stirring speed > emulsifier content > stirring time. (2) Thermal stability evaluation showed that HIACE underwent Ostwald ripening after heating at 90°C, with significant differences in droplet size growth rates. Temperature sweep results indicated that phase transition temperatures were closely related to droplet size: 67°C for droplets smaller than 4μm, 60°C for 4-9μm droplets, and 57°C for droplets larger than 20μm. (3) Storage stability evaluation revealed that during 28-day storage at 25°C, some samples underwent phase separation within 7-28 days, while samples with droplet sizes smaller than 4μm showed no phase separation and minimal droplet size changes, demonstrating excellent storage stability. (4) Freeze-thaw stability evaluation through 1-3 freeze-thaw cycles showed that samples with smaller droplet sizes had oil separation rates of only 0.8%-5%, exhibiting excellent freeze-thaw resistance. Smaller droplet sizes correlated with better freeze-thaw stability due to reduced interfacial area, which decreased the possibility of ice crystal penetration. (5) The established linear regression model indicated that stirring speed, asphalt content, and emulsifier concentration significantly affected droplet size, with a model goodness of fit R^2 of 0.938.

Results demonstrate that HIACE achieves optimal stability when droplet size is below 4μm, corresponding to a phase transition temperature of 67°C, 28-day storage stability, and freeze-thaw mass loss below 5%. This study establishes a quantitative framework that links microstructure with macroscopic stability, providing theoretical guidance for the optimisation of HIACE formulation. The research findings hold significant theoretical importance and practical value for advancing sustainable road construction, establishing a scientific foundation for the industrial application of high-performance emulsified asphalt.

Assessment and Early Warning of Driving Safety Risks on Expressway in Sandstrom

Fang Wang [1], Shixiao Liu [1], Guorui Li [1], Liyi Sun [1], Hao Zhu [1], Honghao Zou [1], Jiayue Xing [1]

[1] School of Civil Engineering and Hydraulic Engineering, Ningxia University, Yinchuan, Ningxia, wangfang@nxu.edu.cn

Graphical abstract (Provide a graphical abstract to summarize this presentation.)

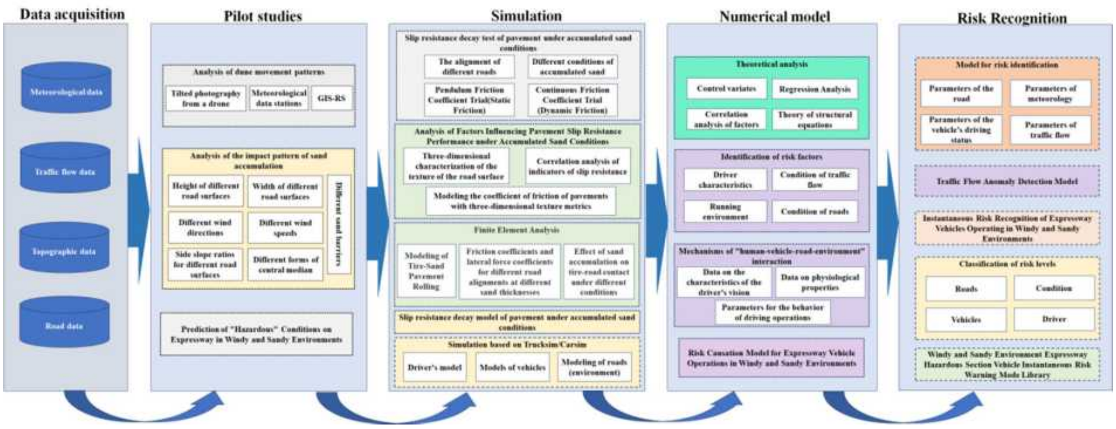

Figure 1 Graphical abstract

1 Objectives and Methodology

1.1 Identify External Factors & Critical Thresholds for Sand Hazards

This objective was addressed by analyzing construction data from the Yinbai and Wuma Expressways (Ningxia sections), collecting oblique photography and meteorological data along both routes, and conducting dynamic analysis of dune movements to pinpoint external drivers (e.g., wind patterns, topography) and establish critical thresholds (e.g., wind speed/duration) for sand drift and accumulation formation on road surfaces.

1.2 Analyze Road Degradation and Vehicle Stability under Sand Accumulation

Through on-site experiments simulating varying sand accumulation conditions, complemented by 3D scanning technology and simulation techniques, this objective investigated degradation patterns of road surface anti-skid performance (e.g., friction loss) and vehicle stability metrics (e.g., lateral control, braking efficiency) to quantify safety impacts.

1.3 Reveal Accident Mechanisms & Develop Risk Identification Methods

By extrapolating traffic scenarios in wind-sand environments, this study analyzed "driver-vehicle-road-environment" interaction mechanisms to identify accident formation rules and influencing factors. Machine algorithm-based methods for instantaneous vehicle risk identification were developed and validated using driving simulation tests integrated with Trucksim simulations.

1.4 Propose Optimal Risk Warning Methods & Safety Strategies

Optimal instantaneous risk warning methods for in-vehicle operation were designed, leading to integrated safety warning strategies for windy/sandy highways. These strategies incorporated real-time risk characteristics, warning mechanism design/activation protocols, and human factors (e.g., driver perception-response patterns) to enhance operational safety.

2 Major results and findings

2.1 Sand Hazard Formation

Analysis identified key external factors driving sand drift and accumulation on the Yinbai and Wuma Expressways—including specific wind dynamics, sand availability, topography (via oblique photography), and road alignment (from construction data). Crucially, critical thresholds for hazard initiation and severity (e.g., wind speed $\geq$ 10 m/s, specific wind direction persistence) were determined through dune movement dynamics and meteorological analysis.

2.2 Impact of Sand Accumulation on Road & Vehicle

On-site experiments, 3D scanning, and simulations quantified severe degradation of road anti-skid performance under sand accumulation, showing friction coefficient reductions up to 40–60%. Concurrently, vehicle stability degradation was characterized by increased lateral deviation (15–30%), elevated rollover risk (particularly for high-CG vehicles), and braking instability, directly correlating with accumulation depth and distribution patterns.

2.3 Accident Mechanisms & Risk Identification

The study revealed complex "driver-vehicle-road-environment" interaction mechanisms causing accidents, identifying key sequences (e.g., visibility drop → adhesion loss → overcorrection) and critical factors (wind gusts > 15 m/s, driver reaction delays > 2s). Machine learning algorithms for instantaneous risk identification were successfully developed and validated using Trucksim-driving simulation co-simulation.

2.4 Safety Warning Solutions

Optimal instantaneous risk warning methods were proposed, integrating real-time detection of hazard characteristics (e.g., friction loss, wind gusts). Comprehensive safety strategies were formulated, combining adaptive warning mechanisms (multimodal alerts triggered 3–5s pre-hazard) with human-centric design (salient auditory cues, minimal cognitive load) to ensure timely driver response in sandstorm conditions.

Research on Runway Life Based on the Size Effect of Slabs

Chunxiang Qi, Associate Professor, Civil Aviation University of China

With the rapid development of the global air transportation industry, airport runways are facing increasing load demands and severe challenges from traditional design theories. According to the statistics of the Civil Aviation Administration of China in 2024, the passenger transportation volume of civil aviation in China reached 620 million in 2023, with a year-on-year increase of 63.7% in aircraft takeoffs and landings. It is expected that the global air passenger volume will increase by about 50% compared to 2019 in 2030. The spacing between the main landing gears of mainstream commercial aircraft in China is generally within the range of 5-10m, while airports both domestically and internationally widely adopt runway panel designs with specifications of 4.5m × 5.0m and 5.0m × 5.0m. Although this traditional small-sized pavement panel can effectively disperse stress, it has problems such as multiple board joints and concentrated wheel loads, which can easily lead to edge breakage, misalignment, and other diseases. Research shows that under the load of heavy aircraft such as A380, the maximum bending and tensile stress in the corner area of 5m × 5m pavement panels can reach 4.8 MPa, far exceeding the strength bearing range of concrete materials.

Increasing the size of the pavement panel can reduce the number of joints by 40% - 60%, significantly reduce the rate of joint defects, and improve construction efficiency by 15% -25%, but it will exacerbate the unevenness of temperature stress inside the panel. In the high temperature environment of summer, the temperature gradient of the 7.5m × 7.5m track panel can reach over 50 ℃/m. After the temperature stress is superimposed with the aircraft load, the area in the panel will become a new critical stress zone. Therefore, how to optimize the size of runway panels to improve runway life under the long-term coupling effect of temperature environment and aircraft load has become a key issue that urgently needs to be solved in the field of airport engineering.

This study focuses on the coupling mechanism between the size effect of pavement panels and temperature stress, and comprehensively uses methods such as elastic layer theory, finite element simulation, and fatigue damage analysis to systematically explore the influence of pavement panel geometric parameters on temperature stress distribution, structural response, and fatigue life. A three-dimensional finite element model considering the coupling of temperature field and load field is constructed, and C3D8R solid elements are used to discretize the pavement structure. The Winkler foundation model is used to simulate the base support effect, and the virtual material layer method is introduced to simulate the joint load transfer effect, in order to analyze the mechanical response of the pavement panel under different working conditions.

Temperature stress analysis was conducted on 12 different sizes (4.5m × 5m to 7.5m × 7.5m) of pavement panels using finite element method, and the results showed that the size and shape of the pavement panels have a significant impact on temperature stress. The temperature stress shows a significant nonlinear growth trend with the increase of equivalent size D: when $D \leq 6$m, the stress growth rate is 0.318MPa/m, mainly dominated by the constraint effect of the base layer; When D ≥ 6m, the growth rate drops to 0.057MPa/m, and the structure enters a "quasi infinite plate" state. Comparing different shapes of pavement panels, it was found that the temperature stress of non square panels is 8.8% higher than that of square panels at the same equivalent size. Therefore, it is recommended to prioritize the use of square panels in designs with D ≤ 6m to reduce stress levels.

The study selects three types of pavement panel sizes, namely 5m × 5m × 36cm, 5m × 5m × 38cm, and 5m × 5m × 40cm, as reference working conditions. Through systematic finite element simulation and quantitative analysis, the study delves into the compensating effect of pavement panel thickness on temperature stress. The results show that when the plate thickness increases from 36cm to 40cm, the temperature stress of the 5.5m × 5.5m track panel can be reduced by 34% -37%; After further thickening to 46cm, the decrease in stress slows down and the marginal benefit significantly decreases. A quantitative relationship model of size thickness stress is established through regression analysis, and the relationship between compensation thickness Δ h and equivalent size D is obtained as Δ h=0.08D+12 (D ≤ 6m), providing a quantitative basis for optimizing pavement structure.

In the study of the coupling effect between temperature and aircraft load, a temperature gradient condition of -30 ℃/m to+30 ℃/m is set, and it is found that the positive and negative temperature gradients exhibit significant asymmetric characteristics in the tensile stress distribution and deflection of the pavement panel. The growth rate of tensile stress at the top of the plate under negative temperature gradient is 44.4% higher than that under positive gradient. When the gradient is -30 ℃/m, the tensile stress at the top of the plate reaches 11.7MPa, while at+30 ℃/m, the tensile stress at the bottom of the plate is 8.1MPa. The deflection response shows that the mid span deflection of the 7m × 7m pavement panel at a gradient of -30 ℃/m is 35.3% greater than that at+30 ℃/m, reflecting the significant influence of temperature gradient direction on structural deformation.

Focusing on the effect of track panel size on runway service life, this study analyzes the load distribution probability, track panel plane size, and track panel thickness increment of different aircraft models from multiple aspects. Based on the probability model of load distribution for A320 and B737-800 aircraft models, it analyzes the fatigue life of pavement panels of different sizes. The results show that the allowable number of actions of the 7.5m × 7.5m track panel under B737-800 load is only 6.9% of that of the 4.5m × 5m panel. After thickness compensation, the allowable number of actions of 7.5m × 7.5m plates loaded on A320 aircraft can be increased by 8.23 times, and on B737-800 aircraft, it can be increased by 3.05 times. This verifies the effectiveness of the design strategy of "increasing pavement size+thickness compensation" and provides important reference for the scientific design and optimization of airport runways.

This study breaks through the limitations of traditional pavement panel design that only considers a single load factor and establishes for the first time a multi parameter coupled analysis model of temperature stress size effect fatigue life. The study reveals the temperature stress distribution characteristics of non square plates, proposes a quantitative relationship model of size stress thickness, and constructs a fatigue life prediction method considering the probability of aircraft load, providing support for differentiated design of multi aircraft operating airports. The application of research results in practical engineering can effectively improve the service life of airport runways and reduce maintenance costs throughout the entire lifecycle by optimizing the size and thickness of runway panels, which is of great significance for promoting technological progress in the field of airport engineering.

Activation Energy Balanced Design Approach for Recycled Asphalt Binder Blends

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Graphical abstract

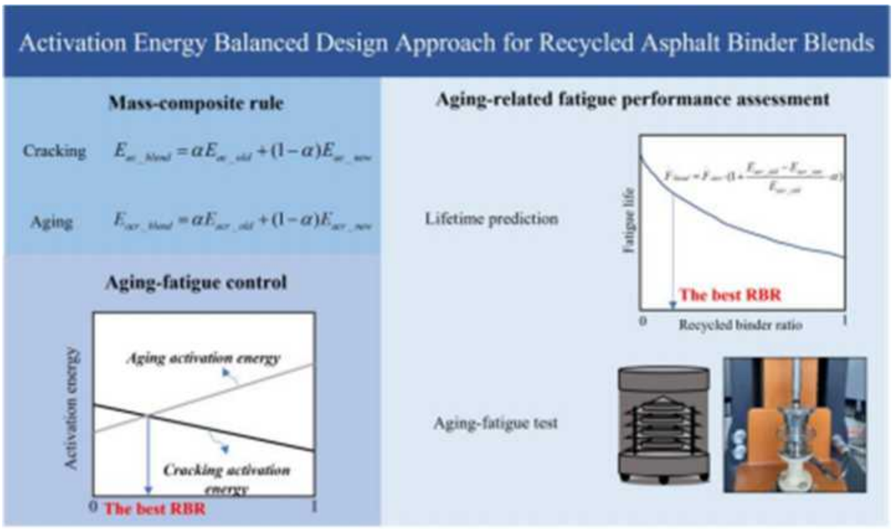

Figure 1 Graphical abstract

1 Objectives and Methodology

When designing an asphalt mixture containing reclaimed asphalt pavement (RAP), the performance issues are of great concern. One of the key challenges is to design a proper recycled asphalt binder blend since the mixture performance is significantly influenced by the binder properties. Considering that fatigue and aging are primary factors controlling the service life of bituminous materials, an activation energy balanced (AEB) design approach for determining the best percentage of RAP binder is proposed. First, the kinetics theory was adopted to model the fatigue process and the aging process of bituminous binder, respectively; meanwhile, the cracking activation energy and aging activation energy were determined using Arrhenius equation to characterize the cracking resistance and aging susceptibility of the binder. Then, inspired by the mass composite rule, the relationship between cracking activation energy and recycled binder ratio (RBR) was established for recycled binder blend; similarly, the change of aging activation energy with RBR was quantified. Moreover, the interaction control towards cracking and aging performance of recycled binder blend was conducted to determine the best RBR at which the blend achieves the same values of both cracking and aging activation energies. Finally, the aging-related fatigue performance of the blend with the best RBR was examined using an activation energy-based lifetime prediction model, and its resistance to aging was also evaluated by aging-fatigue test.

2 Major results and findings

The results show that the aging activation energy of blended binder increases with RBR, while the cracking activation energy decreases as RBR increases, indicating the reduced aging susceptibility and the deteriorated cracking resistance.

The measured activation energies of recycled binder blends are consistent with the calculated mass-composite activation energies, which validates the applicability of mass-composite rule in performance estimation of recycled materials combinations.

As shown in Figure 2, the fatigue life results obtained from the activation energy based lifetime prediction model show a good agreement with the measured fatigue life of different recycled binder blends using strain-controlled fatigue test.

As shown in Figure 3, Figure 4 and Table 1, when the blend achieves the same values of both aging and cracking activation energies, its fatigue life reduces by 10~15% compared to the selected virgin binder, while subject to the same aging condition, the fatigue life of the blend at the best RBR is similar to the virgin binder.

The AEB approach would hopefully ensure that the blend with the best RBR exhibits an acceptable performance in resist both fatigue cracking and oxidative aging.

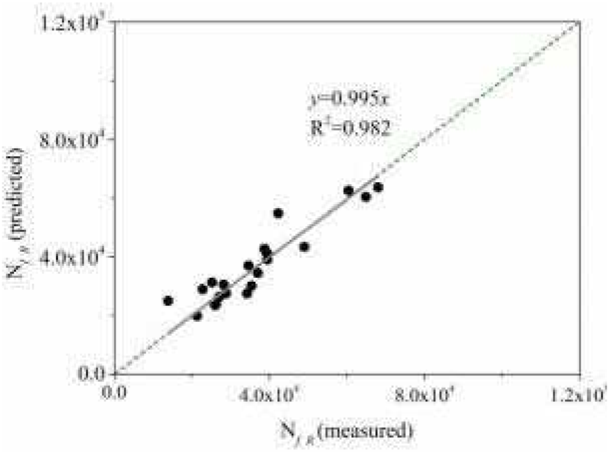

Figure 2 Measured and predicted fatigue life for recycled binder blends

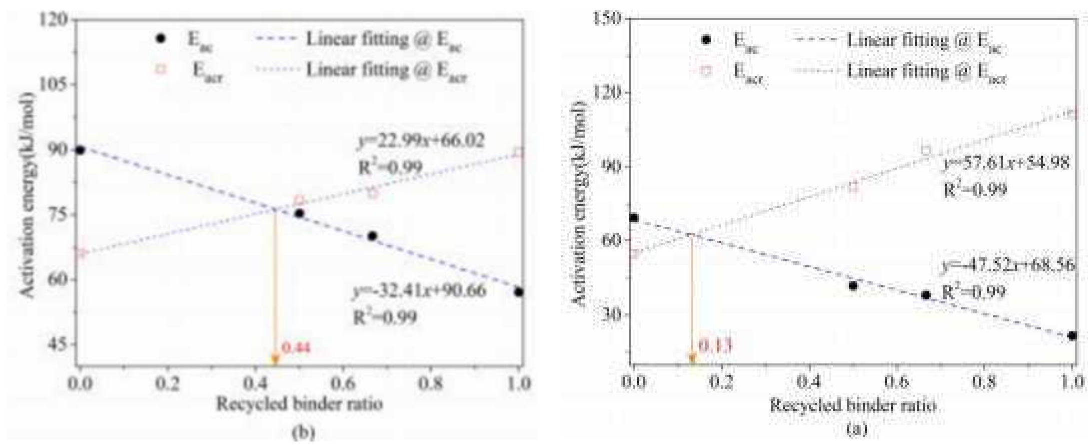

Figure 3 Correlation between aging and cracking activation energies for (a) unmodified recycled binder blends and (b) modified recycled binder blends

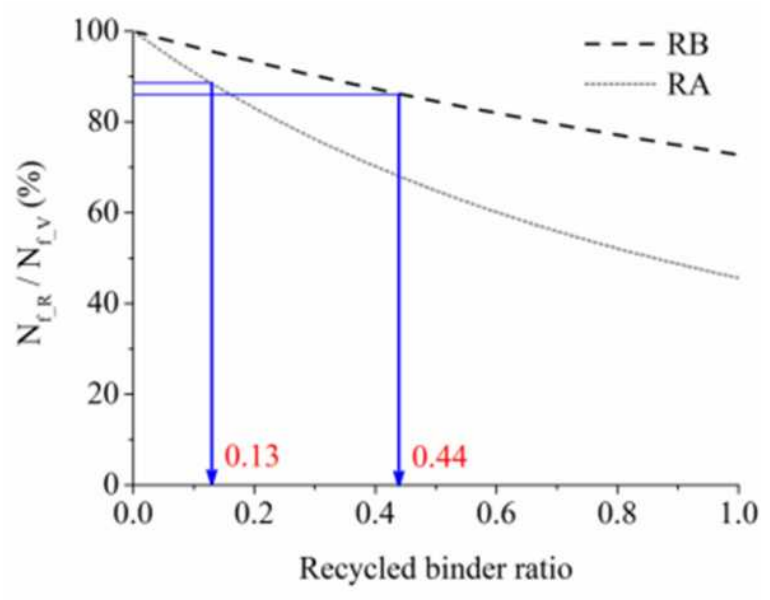

Figure 4 Predicted fatigue life for different recycled binder blends at the b est RBRs (at 20°C)

Table 1 Measure fatigue life for aged blends at the best RBRs (at 20°C)

	Types of bituminous binders		Reduction in fatigue life(%)	
			N_{f50}	N_f
Unmodified	Virgin binder	Pen 70(a)	--	--
	Artificial RAP binder	PA(a)	+135.67	-76.12
	Recycled binder blends	RA11(a)	+103.33	-27.06
		RA21(a)	+335.79	-44.57
		RBA(a)	**+357.12**	**-3.97**
Modified	Virgin binder	SBS-MA(a)	--	--
	Artificial RAP binder	PB(a)	+40.04	-57.33
	Recycled binder blends	RB11(a)	+42.04	-26.89
		RB21(a)	+36.08	-40.98
		RBB(a)	**+105.99**	**-6.04**

Parallel Session J4

Topic: Automated Solutions for Infrastructures

Chair: Hui Yao, Professor, Beijing University of Technology
Cochair: Hailu Yang, Associate Professor, University of Science and Technology Beijing

Introduction:

Under the wave of the global technological revolution, the construction industry is undergoing a profound transformation from "traditional construction" to "smart construction." Digital and intelligent technologies are fundamentally reshaping the entire engineering process, serving as the core drivers for solving complex challenges, enhancing efficiency and quality, and promoting sustainable industry development. This session focuses on "Innovative Applications and Practical Explorations of Intelligent Technologies in Engineering," bringing together cutting-edge achievements from fields such as water resources and hydropower, transportation infrastructure, and structural engineering to establish an interdisciplinary platform for knowledge sharing and collaborative exploration.

The forum will showcase the application of smart construction technologies in major projects: Professor Xiao Sun's team has developed intelligent construction technologies for roller-compacted and conventional concrete, driving construction intelligence through digital integration and equipment innovation; Professor Yanju Hu's AI and 3D imaging-based pavement defect detection system significantly improves identification efficiency and accuracy; Professor Xuhao Cui's finite element analysis reveals the mechanical behavior of ballastless tracks under fault dislocation, providing a scientific basis for track selection; and Professor Yue Liu integrates AI with new materials to achieve breakthroughs in intelligent cable structure design.

These achievements span construction, inspection, structural analysis, and design innovation, demonstrating the practical value and cutting-edge applications of intelligent technologies. They highlight the potential of smart solutions in addressing real-world engineering challenges and reflect cross-disciplinary innovative thinking, offering valuable insights for the industry's intelligent transformation.

Speech:

Lunar "Qinzhidao": Design concept and Development Path of Lunar Surface Roads

Feng Li, Professor, Beihang University

Research and Application of Smart Construction in Water Resources and Hydropower Engineering

Xiao Sun, Professor, Hohai University

Challenges for Al Facilitated Pavement Condition Inspection and Positioning Technologies

Ju Huyan, Professor, Chang'an University

Intelligent Evolution of Cable Structure Design From Computer Aided to AI

Driven

Xuhao Cui, Professor, Beijing Universityof Technology

Effect of fault dislocation on the deformation and damage behavior of ballastless track structures in tunnels

Yue Liu, Professor, University of Science and Technology Beijing

Research and Application of Smart Construction in Water Resources and Hydropower Engineering

Xiao Sun, Professor, Hohai University

This research develops intelligent construction technologies for concrete engineering, integrating digital solutions across key processes. For roller-compacted concrete, innovative tools including stress wave detectors, smart moisture meters and wearable vibrating devices enable real-time monitoring. A GA-BP neural network model evaluates compaction quality, while the implemented digital closed-loop system at Wunonglong Dam enhances quality control and reduces costs.

The study also advances conventional concrete construction through intelligent control systems. BIM-integrated evaluation models and smart vibrating robots with dynamic adjustment optimize compaction quality. Specialized rheology control instruments streamline prefabricated component production. These integrated solutions demonstrate significant improvements in construction efficiency, quality consistency and cost-effectiveness, marking important progress in construction digitalization.

Challenges for AI Facilitated Pavement Condition Inspection and Positioning Technologies

Ju Huyan, Professor, Chang'an University

This research addresses critical challenges in pavement distress detection by developing intelligent solutions to overcome the inefficiencies and high costs of traditional methods. Focusing on rural road assessment where standardized approaches are lacking, we introduce innovative AI and 3D imaging technologies to enhance detection accuracy and efficiency.

Key methodological breakthroughs include: (1) SOAT-enhanced 3D laser stereo imaging for intuitive disease identification and (2) AI-based pixel-level crack segmentation using images from cameras, drones, or inspection vehicles. These approaches significantly outperform conventional 2D techniques. To overcome detection challenges like small distress areas and complex backgrounds, we developed adaptive algorithms (differential evolutionary optimization) and automated data enhancement (AutoAugment/PBA). Our integrated system combines multi-sensor data with EKF (Extended Kalman Filter) fusion and YOLOv8-based mileage correction for precise real-time positioning.

The resulting system achieves pixel-level urban/rural road damage detection with automated evaluation and visualized reporting. Future work will incorporate human-in-the-loop learning and unsupervised techniques to advance predictive maintenance for intelligent, long-life pavement systems.

Intelligent Evolution of Cable Structure Design From Computer Aided to AI Driven

Xuhao Cui, Professor, Beijing Universityof Technology

This research presents a comprehensive advancement in cable structure design, integrating material innovation, computational methods, and artificial intelligence. The study establishes form-finding as the fundamental process for determining equilibrium geometry under prestress while addressing complex multi-objective optimization challenges involving cable parameters and load responses.

Key innovations include the application of CFRP cables in landmark projects like Sanya Stadium's roof, validated through experimental studies, along with the development of novel computational methods such as the precise cable length iteration technique and integrated cooperative form-finding approaches that account for supporting frame behavior.

The research demonstrates cutting-edge AI applications through physics-constrained neural networks for complex spoke-wheel cable-net structures, exemplified by the Suzhou Olympic Sports Center design, and practical implementations of cable force-displacement digital twins. By bridging material science, computational analysis, and intelligent algorithms, this research provides a holistic framework advancing both theoretical foundations and practical applications in modern cable structure engineering. Looking forward, the work highlights AI's transformative potential to revolutionize design workflows, enhance efficiency, and foster new collaborative paradigms between architects and engineers.

Effect of fault dislocation on the deformation and damage behavior of ballastless track structures in tunnels

Yue Liu, Professor, University of Science and Technology Beijing

With the expansion of China's high-speed railway network into geologically complex western regions, an increasing number of tunnels are being constructed through fault zones. This study employs a finite element method incorporating concrete damaged plasticity (CDP) theory to establish a coupled model (total length 130 m) integrating track-tunnel-surrounding rock systems. The model systematically analyzes the mechanical behavior of CRTS II and III slab tracks under normal/reverse fault dislocations (dip angle 60°, displacements 5-25 mm).

Key findings reveal: Under normal faulting, the longitudinal continuity of CRTS II tracks induces significant stress concentration (at 25 mm displacement, the damage variable of track slabs reaches 16 times that of CRTS III), while CRTS III exhibits more uniform stress distribution but greater track irregularity (rail vertical displacement doubles that of CRTS II). Reverse faulting alleviates damage in both track types due to compressive effects. Notably, the interlayer gap between CRTS II's base plate and filling layer at 15 mm displacement expands to 1.7 times that of CRTS III.

These findings provide critical guidance for track selection in fault zones: CRTS III is preferable for damage control, whereas CRTS II better maintains track regularity. Practical engineering applications should optimize selection based on specific geological conditions.

Sponsor: Related Universities and Institutes
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