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Infrastructure Development

Innovations, Challenges and Opportunities

*Edited by Siliang Yang, Qian Zhang
and Farzaneh Tahmoorian*



Infrastructure Development - Innovations, Challenges and Opportunities

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IntechOpen Book Series

Civil Engineering

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Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor



Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

Meet the Volume Editors



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Contents

Preface	XIII
Section 1	
Net-Zero Infrastructure	1
Chapter 1	3
Design and Performance Enhancement of Permeable Pavement Materials: Material Selection, Composition, Structural Design, and Multifunctional Integration in Sponge City Applications – Part 1: Material Foundations: Composition, Functional Modifiers, and Sustainable Integration in Sponge City Infrastructure <i>by Zhexu Xi and Xiaolin Lu</i>	
Chapter 2	29
Design and Performance Enhancement of Permeable Pavement Materials: Material Selection, Composition, Structural Design, and Multifunctional Integration in Sponge City Applications – Part 2: Structural Design and Multifunctional Synergies: Modelling, Performance, and Future Pathways <i>by Zhexu Xi and Xiaolin Lu</i>	
Section 2	
Sustainable Infrastructure Development	57
Chapter 3	59
Perspective Chapter: The Role of Machine Learning in Developing Sustainable and Resilient Interconnected Infrastructure Systems <i>by Basem A. Alkhaleel</i>	
Chapter 4	91
Transportation Infrastructure Health Monitoring <i>by Ebenezer Fanijo, Jian Liu and Taofiq Mohammed</i>	
Chapter 5	123
Assessment of Recycled Waste Materials for Engineering Applications in Turkey <i>by Merve Akbas and Recep Iyisan</i>	

Section 3	
Future Infrastructure Challenges and Opportunities	157
Chapter 6	159
Cool Pavements for the Mitigation of Urban Heat Island (UHI): A Global Perspective	
<i>by Domenico Vizzari, Paulina Leiva-Padilla and Hengwu Hu</i>	
Chapter 7	181
Development of an Accelerated Pavement Testing System: Effect of Various Climatic Factors	
<i>by N.V. Neelima, S. Bhattacharya, Richard Taylor and Dawid D'Melo</i>	
Chapter 8	203
Road Markings for Reliable Visual Guidance and Sustainability	
<i>by Tomasz E. Burghardt</i>	

Preface

As global demand for climate-resilient and sustainable infrastructure continues to rise, future development must incorporate advanced technologies, improved planning, and a strong emphasis on sustainability. However, this progress is often hindered by challenges such as climate change, rapid urbanisation, public resistance, inequitable access, and complex regulatory processes.

This book presents innovative strategies, technologies, and policies to transform infrastructure systems toward a more sustainable future. Specifically, the book presents a comprehensive framework for permeable pavements within the Sponge City concept, focusing on material foundations and advanced structural design supported by life-cycle and smart-sensing approaches. The book also advances sustainable and resilient infrastructure, demonstrating the viability of recycled materials for eco-friendly construction, introducing sensor-based health monitoring for real-time diagnostics and predictive maintenance, and synthesising cool pavement technologies to mitigate urban heat islands, together offering complementary strategies for durability, climate adaptation, and smart infrastructure development. In addition, the book highlights emerging infrastructure challenges and opportunities, including optimizing road-marking materials for improved visibility, durability, and environmental performance, and using machine learning to enhance resource efficiency, enable predictive maintenance, and support adaptive recovery across interconnected systems.

The book, however, seeks to foster dialogue on meeting the UN Sustainable Development Goals (SDGs) while achieving global climate targets and building a strong global economy to shape the next generation of sustainable infrastructure innovation.

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Section 1

Net-Zero Infrastructure

Design and Performance Enhancement of Permeable Pavement Materials: Material Selection, Composition, Structural Design, and Multifunctional Integration in Sponge City Applications – Part 1: Material Foundations: Composition, Functional Modifiers, and Sustainable Integration in Sponge City Infrastructure

Zhexu Xi and Xiaolin Lu

Abstract

Part 1 establishes the material and sustainability foundations of permeable pavements (PPs) within the Sponge City paradigm. It consolidates hydrological-mechanical requirements and embeds them in international and domestic standards that govern infiltration, storage, and structural reliability. The core analysis links composition to pore-scale architecture and durability: gap-graded and stone-on-stone aggregate frameworks to raise connected porosity and stabilize load paths; binder families (cement, porous asphalt, polymer/hybrids) modified with supplementary cementitious materials (SCMs), nanosilica, polymer reinforcement, and surface densifiers to mitigate carbonation, freeze-thaw damage, and aging; and functional additives (hydrophobic agents, adsorptive biochar/layered double hydroxide (LDH), photocatalytic TiO_2) that deliver pollutant attenuation, de-icing resilience, and self-cleaning without sealing macropores. Valorization of industrial by-products and recycled aggregates (RCA, RAP, steel slag) is assessed for carbon reduction and

resource efficiency, alongside performance trade-offs and quality-control routes. X-ray CT-informed packing models and pore metrics (connectivity, throat size, tortuosity) are highlighted as practical levers to reconcile hydraulic conductivity with mechanical resilience. Collectively, Part 1 provides a materials-centric framework that primes the structural design, multiscale modeling, and multifunctional integration developed in Part 2.

Keywords: permeable pavement, Sponge City, pore structure optimization, aggregate-binder design, functional additives, recycled aggregates

1. Introduction

1.1 Background and significance

Rapid urbanization and climate change are intensifying the frequency and magnitude of pluvial flooding, heatwave amplification, and diffuse pollution in the world's cities. Conventional roadways and plazas, which are sealed by dense asphalt or concrete, convert >70% of incident rainfall into runoff, overwhelming legacy drainage networks and exporting contaminants to receiving waters [1]. The economic toll of urban flood events already exceeds US\$40 billion per year and is projected to rise steeply under high-emission scenarios [2], highlighting an urgent need for nature-based stormwater infrastructure that can restore infiltration pathways while sustaining vehicular and pedestrian demand [3, 4].

China's "Sponge City" program has emerged as the most ambitious response to this challenge, reimagining the built environment as a hydrologically active matrix capable of absorbing, storing, and reusing at least 70% of annual precipitation [5, 6]. Within this paradigm, permeable pavements (PPs) represent a cornerstone technology: they retrofit directly into hardscape, offer immediate hydraulic relief, and interact synergistically with other green infrastructure, such as bioswales and green roofs. Their performance, however, hinges on a delicate balance between two often-competing requirements: first, a highly connected pore network is needed to achieve initial infiltration rates of $1\text{--}10\text{ mm s}^{-1}$ and maintain flow under repeated clogging cycles; second, the pavement must withstand axle loads of up to 80 kN, freeze-thaw cycling, and chemical attack over design lives of two decades or more.

Despite three decades of incremental progress, current permeable mixtures still suffer from premature clogging, suboptimal mechanical stiffness, and limited functional integration. For example, field surveys reveal that infiltration capacity can decline by 50–80% within the first 5 years of service under moderate traffic, owing to sediment sealing and biofilm growth [7–9]. Moreover, most commercial systems treat hydraulic and structural optimization as separate tasks, neglecting the multiscale coupling between aggregate morphology, binder chemistry, and load transfer through irregular pore walls [10, 11]. These gaps impede wider deployment, particularly in retrofits where pavement thickness and maintenance budgets are constrained.

Fundamental advances in material design, multiscale modeling, and smart sensing now create an unprecedented opportunity to transcend these limitations. High-resolution X-ray micro-computed tomography (CT), coupled with discrete-element simulations and computational fluid dynamics, can resolve pore connectivity and stress fields with micrometer precision, enabling data-driven tailoring of gradation envelopes and binder formulations [12–14]. Meanwhile, the incorporation of

phase-change inclusions [15–17], photocatalytic [18] or NO_x-scavenging fillers [19], and piezoelectric fibers that harvest traffic-induced strain energy [20–22] promises multifunctionality, including cool-roof-level albedo, acoustic damping, and self-powered monitoring, without sacrificing mechanical integrity. Embedding distributed fiber-optic or capacitive sensors could further deliver real-time diagnostics of clogging progression and structural health, transforming permeable pavements from passive infrastructure into adaptive, cyber-physical systems.

The present chapter, therefore, aims to synthesize the dispersed body of knowledge on permeable pavement science—spanning hydrology, materials engineering, and urban ecology—and to chart a coherent pathway toward next-generation, multifunctional pavements that meet the stringent demands of Sponge City implementation worldwide. By integrating state-of-the-art experimental evidence with advanced numerical frameworks, we seek to clarify the mechanisms that limit current performance, identify leverage points for improvement, and outline research priorities that align with the United Nations Sustainable Development Goals [23] on resilient infrastructure and sustainable cities. In this case, we intend to provide both a conceptual scaffold and a practical toolbox for researchers, practitioners, and policymakers striving to mainstream permeable pavements as a keystone of climate-adapted urban design.

1.2 Chapter structure and core issues

This chapter is structured to systematically address the multifaceted scientific and engineering challenges inherent in the design, optimization, and application of permeable pavement materials, particularly within the context of emerging sponge city initiatives. In response to the escalating demands for sustainable urban drainage systems and climate-resilient infrastructure, this work adopts an integrative approach, linking fundamental materials science, fluid mechanics, and environmental engineering with applied technological innovations.

The chapter begins by elucidating the functional requirements of permeable pavements under the sponge city paradigm, providing a comprehensive overview of hydrological, mechanical, and ecological considerations. It subsequently delves into material selection, focusing on aggregate gradation, binder chemistry, and the incorporation of functional additives. Emphasis is placed on the interplay between pore structure and the dual objectives of infiltration capacity and mechanical integrity, which remain central to the durability and performance of permeable pavements.

A significant portion of the chapter is dedicated to the state-of-the-art methodologies for pore structure optimization and permeability enhancement, combining advanced numerical simulations with laboratory-based characterizations. Here, the discussion highlights the importance of balancing interconnected porosity with sufficient load-bearing capacity, a challenge compounded by the heterogeneous and dynamic nature of urban environments.

Building on these foundations, the chapter explores contemporary structural design strategies aimed at maximizing both hydraulic functionality and mechanical resilience. Life-cycle performance assessment and maintenance considerations are also addressed, underscoring the need for holistic evaluation frameworks in real-world applications.

Further, the integration of multifunctional properties, such as thermal regulation, noise mitigation, and pollution attenuation, is critically reviewed. The role of permeable pavements as active components in urban climate adaptation and

ecological restoration is emphasized, in line with the broader vision of sponge city infrastructure.

In anticipation of future developments, the chapter identifies emerging trends in smart sensing, adaptive materials, and the utilization of recycled or low-carbon constituents. The prospects for intelligent, self-monitoring pavement systems are discussed, along with the challenges of standardization, scalability, and long-term sustainability.

Collectively, this structure is designed to provide a holistic and forward-looking synthesis, delineating both the current state of the art and the pressing scientific questions that must be addressed to enable the next generation of multifunctional permeable pavements. Key issues highlighted throughout include:

- i. the optimization of material composition for synergistic hydraulic and mechanical performance;
- ii. the development of predictive models that bridge laboratory results with field performance;
- iii. the integration of multifunctional and smart technologies; and
- iv. the alignment of technical innovations with urban ecological and policy objectives.

1.3 Overview of Part 1

Part 1 of this chapter establishes the material science and sustainability foundations for permeable pavement systems within the Sponge City paradigm. It synthesizes the hydrological, mechanical, and ecological performance requirements that govern the viability of permeable pavements and contextualizes these within international and domestic design standards. The subsequent sections explore the compositional strategies that underpin performance optimization, including aggregate gradation, binder chemistry, functional fillers, and the valorization of industrial byproducts and recycled aggregates.

By integrating advances in pore structure modeling, durability enhancement, and multifunctional additives, Part 1 delineates the critical pathways through which material innovation can reconcile hydraulic conductivity with mechanical resilience. Particular emphasis is placed on the coupling of material selection with circular economy objectives, thereby aligning engineering practice with low-carbon, resource-efficient urban development. Collectively, the discussions in Part 1 provide both a conceptual framework and a technical reference for designing permeable pavement materials that function not only as drainage devices but also as multifunctional, climate-adaptive components of Sponge City infrastructure.

2. Performance requirements from the perspective of Sponge City development

2.1 Concept and objectives of sponge cities

The sponge city paradigm reimagines urban fabric as an active hydrological interface designed to absorb, store, convey, and purify precipitation in ways that emulate

predevelopment catchments [24]. First articulated in China's national guidelines in 2015 and subsequently echoed in policy frameworks across Asia, Europe, and North America [25], the concept arose from the recognition that conventional gray drainage infrastructure (e.g., oversized pipes, concrete channels, and detention basins) cannot alone mitigate the compound stresses of climate-driven rainfall extremes, urban heat amplification, and aquatic ecosystem degradation.

At its core, a sponge city strives for hydrological neutrality: post-development stormwater runoff volume, peak flow, and pollutant load should approximate those of the site's natural antecedent. Achieving this neutrality demands a distributed mosaic of nature-based solutions, including permeable pavements, bio-retention swales, green roofs, and restored water bodies, integrated from street scale to metropolitan basin [26]. These measures collectively promote four interlocking objectives:

- *Infiltration and aquifer recharge.* By enhancing near-surface percolation and shortening overland flow paths, sponge infrastructures attenuate flood peaks and replenish shallow groundwater, thereby strengthening urban drought resilience.
- *Water quality amelioration.* Filtration through vegetated or porous media removes suspended solids, nutrients, heavy metals, and microbial contaminants with documented load-reduction efficiencies of 30–90% depending on design and climatic context [27, 28].
- *Thermal regulation and microclimate improvement.* Evapotranspiration from wetted surfaces and vegetation generates latent-heat sinks that can reduce local air temperatures by up to 2°C during heatwaves, mitigating the urban heat-island effect [29].
- *Ecological and social co-benefits.* Restored hydrological connectivity supports biodiversity corridors, while accessible blue-green spaces promote public well-being, property-value uplift, and climate-adaptation literacy among residents [30].

To operationalize these goals, contemporary guidelines advocate a multiscale performance hierarchy: individual measures must meet local infiltration and load-bearing criteria; neighborhood clusters must achieve target runoff coefficients (typically ≤ 0.3 for a 2-year design storm); and the citywide network must reconcile competing land use, economic, and cultural priorities through adaptive governance mechanisms such as sponge city master plans and dynamic performance metrics [31]. Crucially, quantitative targets are increasingly coupled with life-cycle carbon accounting and circular economy principles, aligning the sponge city vision with broader agendas for net-zero and resilient urban development [32].

Collectively, these ambitions position the sponge city not merely as an engineering retrofit but as a systemic reframing of how cities co-evolve with water under accelerating climatic uncertainty.

2.2 Functional positioning of permeable pavements

Permeable pavements (PPs) occupy a pivotal niche within the broader palette of nature-based solutions deployed in Sponge City strategies. Acting as distributed,

surface-level hydrological regulators, they mediate the interface between the built environment and the underlying soil-water continuum, thereby complementing subsurface infiltration galleries, vegetated swales, and detention basins [33–35]. Their functional remit can be distilled into four partially overlapping domains: (i) hydrological moderation, (ii) structural load sharing, (iii) environmental co-benefits, and (iv) systems integration and scalability.

Hydrological moderation. The foremost purpose of a PP is to intercept rainfall at the point of contact, facilitating rapid vertical percolation and temporary storage within an open-graded sub-base [33, 35]. This mitigates peak discharge, shortens hydrograph response, and replenishes shallow groundwater. The process hinges on sustaining a connected macroporous network (total porosity $\approx 15\text{--}25\%$; effective porosity $>12\%$) and preserving hydraulic conductivity above the regulatory threshold (typically $10^{-3}\text{--}10^{-4} \text{ m s}^{-1}$ under service loads). In mixed precipitation regimes, the pavement must also tolerate cyclic saturation, maintaining infiltration rates after hundreds of freeze-thaw and sediment loading cycles [36]. Consequently, functional positioning entails not merely initial permeability but the capacity to resist dynamic clogging while providing infiltrative resilience over decadal horizons.

Structural load sharing. Unlike infiltration trenches, PPs must simultaneously perform as primary traffic surfaces. Their design therefore reconciles contradictory demands: the void ratio required for permeability and the contact stiffness needed to distribute axle loads without excessive rutting or fatigue cracking [37]. Load paths are managed through aggregate interlock in surface and base courses, coupled with geosynthetic reinforcement where subgrade modulus falls below $\sim 50 \text{ MPa}$ [38]. Thus, PPs function as hybrid hydraulic-mechanical devices, relying on finely tuned gradation envelopes and binder systems to maintain bearing capacity ($\geq 5 \text{ MS-ESALs}$ for light-medium traffic) without sacrificing infiltration.

Environmental co-benefits. Beyond runoff control, PPs deliver ancillary ecosystem services. Evapotranspiration from retained water and high albedo surface finishes lower near-surface air temperatures by $0.5\text{--}2^\circ\text{C}$ in summer months, moderating urban heat islands [39, 40]. The tortuous pore network attenuates tyre-pavement noise by $2\text{--}7 \text{ dB(A)}$, while the underlying filtration bed traps suspended solids and fosters biogeochemical degradation of hydrocarbons, nutrients, and trace metals [41]. When amended with photocatalytic or sorptive additives, PPs can further reduce diffuse pollution loads, positioning them as multifunctional green-infrastructure assets rather than single-purpose drainage elements [34].

Systems integration and scalability. In the Sponge City hierarchy, PPs operate at the plot-to-street scale, yet their cumulative hydrological impact is district-wide [35]. They are readily retrofitted during routine resurfacing cycles, offering a low-disruption pathway to augment legacy sewers and balance-of-system detention. Integration with permeable shoulders, green roofs, and smart sensors enables adaptive, networked control of storage availability and pollutant removal. Crucially, their modularity supports staged implementation, aligning capital expenditure with incremental resilience targets and allowing data-driven optimization as real-world performance feedback accrues.

Collectively, these attributes situate permeable pavements as cornerstone components in climate-adaptive urban drainage portfolios—materials that are simultaneously structural, hydraulic, and ecological. Their functional positioning is therefore defined less by a single metric (e.g., infiltration rate) than by their ability to maintain a suite of coupled performances under evolving environmental and loading regimes.

2.3 International and domestic standards and key design criteria

The development and application of permeable pavement systems are guided by a series of technical standards and regulatory frameworks aimed at ensuring performance reliability, structural integrity, and environmental sustainability. These standards typically straddle two regulatory worlds: pavement engineering (structural safety, durability, skid resistance) and stormwater management (run-off reduction, groundwater recharge, water quality) [41]. Harmonizing metrics across these domains is essential to predictable field performance, life-cycle cost control, and compliance with water regulations. Contemporary guidance now links layer thickness to both hydrologic storage (design storm, drain-down time) and structural load category and prescribes field verification of surface infiltration over service life [42].

2.3.1 Core test methods for hydraulic function

Standardized field infiltrometer procedures underpin acceptance testing and condition assessment:

- ASTM C1701/C1701M determines the field water infiltration rate of in-place pervious concrete using a sealed ring, specified water volume, and measured drain time. It is the baseline method for monolithic pervious concrete slabs [43].
- ASTM C1781/C1781M adapts the procedure for permeable unit pavement systems (interlocking concrete, grid, or clay pavers) where flow enters primarily through joints/voids; it adds provisions for securing the ring to discontinuous surfaces [44].
- Many agencies apply the ASTM C1781 timing-rate relationship to trigger surface cleaning or rehabilitation, reflecting the sensitivity of jointed systems to clogging [45, 46].
- EN 12697-19 provides a laboratory method for measuring vertical and horizontal permeability of cylindrical bituminous (porous/OPA) specimens—used in mix design quality control and forensic evaluations [47].
- Design documents routinely call for correlating laboratory permeability/void structure with field ASTM C1781 infiltration tests to manage scale effects [41, 42].

2.3.2 International design frameworks and guidelines

The FHWA PICP Tech Brief synthesizes hydrologic and structural design: open-graded bedding/base/sub-base layers provide temporary storage sized to targeted storm capture (often regulatory percentiles such as the 85th percentile depth), with underdrains where subgrade infiltration is insufficient; drain-down is typically required within 48–72 h [41]. Minimum unit thicknesses of 80 mm for vehicular and 60 mm for pedestrian areas, and attention to groundwater separation (~0.6 m minimum recommended) are highlighted.

ASCE/T&DI/ICPI 68-18 (national US consensus standard) codifies these practices—site suitability screening (rainfall statistics, soil group, groundwater,

setbacks), mechanistic-empirical sub-base thickness tables derived from full-scale load testing, and integrated maintenance planning [41, 48].

State/agency manuals (e.g., Minnesota Stormwater Manual) instruct designers to take the thicker of hydrologic storage or structural thickness calculations, to flatten subgrade slopes (<1% preferred), and to apply safety factors to measured soil infiltration when sizing reservoirs and deciding on underdrains [42].

Within the European context, the Comité Européen de Normalisation (CEN) issues standards, such as EN 12697, that prioritize both mechanical integrity—encompassing resistance to frost heave and sustained loading—and long-term resilience to clogging phenomena [49]. Additionally, the sustainable drainage systems (SuDS) approach codifies integration into urban hydrological networks, emphasizing multifunctional ecosystem services [50]. In Japan and Australia, technical guidelines are further adapted to local risk factors, including seismicity and episodic high-intensity rainfall, with corresponding material and structural adaptations [51, 52].

2.3.3 Material and layer specifications (selected benchmarks)

Key dimensional and material criteria recur across guidance documents:

- *Surface course thickness:* Interlocking concrete units ≥ 80 mm in vehicular areas; 60 mm common for pedestrian use [45, 53].
- *Joint width and aggregate:* Typical 4.5–13 mm ($\approx 3/16$ – $1/2$ in.) joints receive clean, uniformly graded permeable aggregate (e.g., ASTM No. 8; finer gradations for narrower joints) to maintain infiltration and interlock; joint width capped (~ 13 mm) for accessibility compliance [53].
- *Reservoir gradations and thickness:* Open-graded base/sub-base (ASTM No. 57, 2, 3, or 4 stone families, regionally adjusted) sized first for the required water storage volume, then checked for structural loads; the controlling (greater) thickness governs construction [42, 45].
- *Drain-down infrastructure:* Underdrains and overflow appurtenances placed within the base/sub-base to evacuate excess water when soil infiltration is slow; design must account for traffic loading and maintenance access [45, 54].

2.3.4 Performance thresholds and maintenance triggers

Routine post-construction monitoring uses field infiltration as a leading indicator of hydraulic function:

- Industry guidance flags surface cleaning when measured rates fall below ~ 20 in./h (≈ 508 mm/h); more aggressive action is recommended immediately if < 20 in./h or if slopes $> 2\%$ exhibit < 40 in./h, because runoff bypass and icing risks increase sharply [53, 55].
- Design manuals emphasize integrating maintenance access (vacuum sweeping, regenerative air) at the planning stage to sustain infiltration over the design life [42, 55].

2.3.5 Domestic (China) standards landscape

China has issued a suite of municipal engineering standards differentiated by surface type:

- CJJ/T 135 (2009, 2023 partial revision) [56, 57]—material selection, mixture parameters, and structural detailing for permeable cementitious pavements; recent revisions clarify materials performance and integration with other municipal codes.
- CJJ/T 188-2012 [57, 58]—governs permeable brick pavements (segmental), including layer build-ups (surface, leveling, permeable base, optional sub-base) and material specs.
- CJJ/T 190-2012 [59]—applies to permeable asphalt in new/rehabilitated urban roads; covers mix design, construction, acceptance, and maintenance.
- Recent local Sponge City-oriented specifications (e.g., Nanjing DB3201/T1150-2023) set quantitative acceptance limits: permeable brick $k \geq 0.2$ mm/s, British Pendulum Number (BPN) ≥ 60 for skid, abrasion ≤ 35 mm, and strength classes scaled to traffic (vehicular ≥ 50 MPa avg. compressive; pedestrian ≥ 40 MPa). Layer combinations, drainage detailing (e.g., internal drains sized $\geq 2 \times$ expected inflow), and freeze-thaw/salt resistance test requirements are provided [57].
- Sponge City construction/design standards (e.g., Beijing municipal guidance) require permeable surfacing in suitable pedestrian, bicycle, and plaza areas, linking pavement selection to broader runoff retention, storage, and overflow control strategies mandated under national Sponge City policy frameworks [57, 60].

2.3.6 Adapting standards to site hydrology and subgrade

Across jurisdictions, a convergent theme is contextualization: subgrade infiltration capacity, groundwater depth, frost susceptibility, and contributing drainage area govern whether designs are full-, partial-, or no-infiltration systems; sub-base depths increase over low-permeability or weak soils, sometimes coupled with impermeable liners to manage shrink-swell clays; and underdrain elevations are tuned to achieve mandated drawdown times (commonly ≤ 72 h) while protecting pavement structure [42, 54, 57].

2.3.7 Practical synthesis: Minimum dataset for design submittals

Given the diversity of standards, a defensible design package should, at minimum, document (i) governing code(s) adopted; (ii) target design storm or regulatory capture metric; (iii) measured and design-factored soil infiltration rate; (iv) groundwater/bedrock separation; (v) structural load category and resulting layer thicknesses; (vi) specified surface infiltration acceptance threshold and maintenance triggers; and (vii) evidence that materials (pavers, mixes, aggregates) meet relevant product specifications [55]. Aligning these submittal elements with the applicable regional

standard (e.g., ASCE 68-18, BS 7533-13, or CJJ/T series) reduces approval risk and improves long-term performance tracking [48, 56, 61].

3. Material composition and selection

3.1 Aggregates: Gradation and physico-mechanical properties

The aggregate skeleton governs both the hydrological and load-bearing performance of permeable pavements. Unlike dense asphalt or concrete mixtures, where the binder phase dominates microstructural continuity, permeable systems rely on a well-interlocked yet deliberately discontinuous aggregate matrix that creates a stable network of interconnected voids. Optimizing this skeleton, therefore, requires a dual focus: (1) particle size distribution (PSD), which sets the macropore architecture and infiltration kinetics, and (2) the intrinsic physico-mechanical properties of individual particles, which dictate strength, abrasion resistance, and long-term durability.

3.1.1 Gradation principles for void connectivity

Permeability emerges when the fine fraction is suppressed sufficiently to prevent pore blockage, while the coarse fraction is closely packed to resist consolidation under traffic. Classical empirical guidelines such as the 0.45-power curve offer a first approximation, yet fail to address the conflicting goals of permeability and rutting resistance. Contemporary design, therefore, pivots to gap-graded or stone-on-stone contact frameworks.

- Gap-graded blends intentionally omit intermediate sizes (typically 4.75–9.5 mm) to increase the volume of air voids to 15–25%, thus supporting infiltration rates of 1×10^{-3} – $5 \times 10^{-3} \text{ m s}^{-1}$ [62].
- Stone-on-stone contact mixtures adopt a coarse aggregate content above the Voids in Coarse Aggregate (VCA) threshold, ensuring that the fine fraction remains suspended without filling the primary void skeleton [62]. This configuration minimizes post-compaction densification and maintains stable voids under cyclic loading.

Particle size distribution (PSD) is a principal parameter influencing not only the packing density and interparticle contact but also the continuity and connectivity of voids within the matrix. An open-graded aggregate system, typically characterized by a gap-graded or uniformly graded PSD, promotes the formation of interconnected macropores that enable high infiltration rates and reduce the risk of surface runoff. Conversely, excessively fine or well-graded systems tend to reduce porosity and may result in premature clogging, thereby undermining the hydrological benefits that permeable pavements are intended to provide. Optimal gradation curves seek to maximize both load-bearing capacity and permeability, but an inherent trade-off exists, necessitating context-specific tailoring.

Numerical packing models, including the compressible packing model (CPM) and the modified Alfred model, allow designers to simulate multimodal distributions and predict both maximum packing density and resultant pore connectivity. When calibrated against X-ray computed tomography (CT) data, these models achieve pore

size distribution predictions within $\pm 5\%$ of experimental observations [63], enabling rapid virtual prototyping of aggregate blends before laboratory trial mixes.

3.1.2 Hydraulic metrics derived from gradation

Gradation controls three critical hydraulic descriptors:

- Effective porosity (n_e): the interconnected void volume accessible to flow, typically 0.75–0.9 of total porosity in well-designed systems.
- Mean pore throat diameter (d_p): ranging from 0.5 to 2.0 mm; values below 0.3 mm markedly increase clogging susceptibility.
- Hydraulic conductivity (k): an exponential function of n_e and d_p ; field measurements commonly span 0.001–1 cm s⁻¹ but decline logarithmically with sediment accumulation.

Balancing these metrics necessitates iterative adjustment of the fines content (<2.36 mm). While ISO standards limit fines to <10% by mass, recent field trials demonstrate that incorporating up to 15% ultra-clean micro-fillers with hydrophobic surface treatments can fill contact voids without compromising flow, thereby enhancing load transfer and reducing mix segregation during placement [64].

3.1.3 Physico-mechanical requirements of aggregate particles

Under vehicular and climatic loading, the coarse fraction is the primary stress carrier. Key material indices include:

- *Los Angeles abrasion value (LAAV)*—should not exceed 25% mass loss for high-traffic permeable asphalt; lower thresholds (<20%) are recommended for cold regions prone to studded tyre abrasion [65].
- *Micro-deval coefficient*—provides a complementary measure of wet abrasion; values <15% correspond to extended service life in freeze-thaw environments [66].
- *Crushing strength (aggregate crushing value/aggregate crushing index, ACV/ACI)*—a 10% fines value >150 kN [65] ensures sufficient resistance to rutting and static indentation.

These properties entail hardness, abrasion resistance, crushing strength, and shape characteristics, which fundamentally govern the load distribution and deformation behavior under traffic loading. High-quality aggregates with superior LAAVs, low water absorption, and angular morphology confer enhanced interlock and shear resistance, mitigating the risk of rutting, settlement, and aggregate breakdown over time. Angular particles, as opposed to rounded particles, not only improve structural interlocking but also contribute to the stability of the porous skeleton, albeit at the expense of potential workability issues during mixing and placement.

Mineralogical composition further modulates durability in aggressive urban environments. Basaltic and granitic aggregates exhibit superior hardness and chemical inertness, whereas limestone, though easily available, may undergo dissolution in

acidic runoff, increasing fines generation. Siliceous gravels offer adequate hardness but can be susceptible to alkali-silica reaction (ASR) in cement-bound permeable concrete; mitigation strategies include LiNO_3 admixtures or partial replacement with non-reactive metakaolin. Additionally, the presence of microcracks or inherent flaws in the aggregate structure can serve as initiation sites for mechanical degradation, ultimately compromising both mechanical and hydraulic longevity.

3.1.4 Surface texture and morphology

Contact mechanics within the aggregate skeleton are sensitive to particle angularity and sphericity. Image-based indices, extracted *via* 3D laser scanning or CT segmentation, correlate higher angularity with superior shear interlock but also elevated compactive effort. A “well-textured” aggregate ensemble, defined as having a form factor (FF) between 0.7 and 0.9 and an angularity index (AI) >200 , achieves optimal trade-offs, combining high internal friction with manageable workability [63]. For binder-rich permeable concrete, a slightly smoother surface (FF ≈ 0.95) promotes uniform paste coating and reduces binder pocket formation.

3.1.5 Sustainability considerations and alternative sources

To align with circular economy targets, growing attention is directed toward recycled concrete aggregates (RCAs) and industrial byproducts. While RCA typically presents elevated water absorption (5–10%), pre-saturation or carbonation treatments can reduce porosity and restore mechanical parity with virgin rock. Steel slag, characterized by high angularity and density, enhances skid resistance but requires aging to stabilize volumetric expansion associated with free CaO phases [67, 68]. Lifecycle analyses reveal that substituting 30% of virgin coarse aggregate with RCA lowers embodied energy by 12% and CO_2 equivalents by 18% [67], without statistically significant loss in permeability or compressive strength.

In summary, the careful design of aggregate properties—through the controlled manipulation of particle size distribution and the selection of physically robust and chemically stable sources—underpins the successful implementation of permeable pavements in urban drainage systems. Future directions may include the use of recycled aggregates and the development of engineered gradations informed by advanced simulation and machine learning techniques, further aligning material design with sustainability and performance imperatives [69].

3.2 Binders: Cement, asphalt, polymers, and their modifications

The binder phase governs both the mechanical integrity and the long-term hydrological functionality of permeable pavements. Whereas aggregates furnish skeletal strength, binders regulate interparticle bonding, pore continuity, and resistance to environmental stressors. This section synthesizes the current understanding of three major classes—hydraulic cements, asphaltic binders, and polymer systems—and highlights contemporary modification strategies aimed at reconciling hydraulic conductivity with structural durability [70].

Cement, particularly ordinary Portland cement (OPC), is extensively used as the primary binder in permeable concrete and pervious mortar. The hydration of cement generates a rigid matrix that provides adequate load-bearing capacity while encapsulating interconnected pores for water infiltration. The macroscopic permeability of

these mixes is dictated by paste content (<15 vol.%) and water-binder ratio, which together define capillary choke points at the interaggregate necks. Empirical evidence indicates an exponential decline in compressive strength when the targeted void ratio surpasses ~25%, underscoring the need for judicious gradation control [71]. However, the intrinsic brittleness and susceptibility to shrinkage cracking in cement-based permeable pavements remain critical limitations.

Supplementary cementitious materials (SCMs) such as ground-granulated blast-furnace slag and Class F fly ash are routinely introduced (5–35 wt.% replacement [72]) to lower the clinker factor, mitigate autogenous shrinkage, and enhance sulfate resistance. Their latent hydraulic and pozzolanic reactions refine the calcium-silicate-hydrate gel, densifying the microporous matrix without occluding the macropores responsible for infiltration. More recently, nano-silica dispersions (≤ 3 wt.%) have been employed to accelerate early-age strength while suppressing efflorescence, albeit at a marginal cost to permeability [73].

Carbonation-induced pH drop—which accelerates in open-pore systems—remains a durability concern. Surface impregnation with silane oligomers or lithium silicate densifiers forms a hydrophobic, yet vapor-permeable, barrier that retards CO₂ ingress without adversely affecting drainage [74]. Freeze-thaw resistance is commonly addressed *via* entrained air (target L/h $\approx$ 4–6% [75]), although excessive foaming can exacerbate abrasion under traffic.

Asphalt binders, commonly applied in porous asphalt mixtures, impart notable flexibility and resilience under traffic-induced stresses and thermal fluctuations [70]. The viscoelastic nature of asphalt enables the dissipation of stresses, mitigating fatigue and rutting, which are common failure modes in permeable pavements. Nevertheless, conventional asphalt binders are vulnerable to oxidative aging, which can induce brittleness, clogging, and loss of permeability over time [76]. To address these challenges, polymer-modified asphalts (PMAs), crumb rubber, and bio-based modifiers have been explored. These additives enhance the elasticity, aging resistance, and hydrophobicity of the binder matrix, promoting sustained infiltration capacity and durability. Furthermore, warm-mix asphalt technologies and rejuvenators have been developed to lower processing temperatures and enable the recycling of reclaimed asphalt pavement (RAP), further aligning permeable pavement construction with environmental sustainability goals [71, 77].

Polymeric binders, including both synthetic (e.g., epoxy resins, polyurethane) and natural polymers (e.g., lignin, starch derivatives), offer an alternative approach for the fabrication of high-performance permeable pavements. Polyurethane-bound permeable pavements, in particular, have demonstrated superior mechanical strength, elasticity, and abrasion resistance, along with high water permeability [78]. The inherent versatility of polymer systems allows for the tailoring of pore structure and surface functionality, such as self-cleaning or photocatalytic properties, through the incorporation of functional additives [79]. Hybrid binders—combining polymers with cementitious or bituminous matrices [80]—exhibit synergistic effects, balancing stiffness, toughness, and permeability.

Recent innovations have also focused on the development of environmentally friendly and low-carbon polymeric binders. For example, bio-based polyurethanes derived from renewable resources and biodegradable polymers are emerging as promising candidates for next-generation permeable pavements [81]. The integration of smart polymers capable of self-healing or responding to environmental stimuli [82] is an area of active investigation, with significant implications for the durability and adaptability of permeable pavement systems in dynamic urban environments.

Across all binder families, multifunctionality is being pursued through targeted micro- and nano-scale interventions. Binder engineering for permeable pavements demands a nuanced balance between rheological, chemical, and environmental attributes. Hydraulic cements excel in compressive performance but require pore-scale tuning and surface treatments to offset carbonation and freeze-thaw stress. Asphaltic binders deliver constructability and flexibility, yet necessitate polymer reinforcement and proactive maintenance to curb oxidative raveling. Polymer and hybrid binders offer compelling multifunctionality but await cost reductions and standardization. Looking ahead, integrative strategies—combining renewable SCMs, smart nano-additives, and adaptive self-healing chemistries—are poised to unlock the next generation of resilient, climate-positive permeable pavements suitable for Sponge City infrastructures.

3.3 Additives and functional fillers

PPs increasingly function as chemically active interfaces, mediating mass and energy exchanges beyond mere water infiltration. To endow the matrix with such reactivity without compromising structural integrity, a new generation of hydrophobic, adsorptive, and photocatalytic modifiers has been engineered and tailored to asphalt- and cement-based binders.

Hydrophobic modifiers aim to decouple capillary rise from gravitational infiltration, ensuring that water penetrates rapidly through the interconnected macropores while liquids of higher viscosity—or dissolved deicing salts—are impeded from lodging within the pore walls. Organosilane and fluorinated acrylate emulsions are routinely sprayed onto freshly laid surfaces, forming a nanometric self-assembled monolayer that lowers surface free energy to $<20 \text{ mN m}^{-1}$. More recently, silica or TiO_2 nanoparticles grafted with short-chain alkyl phosphonates have been wet-mixed into polymer-modified asphalt, generating super-hydrophobic contact angles ($>150^\circ$) that persist after 10^5 wheel passes and 300 freeze-thaw cycles. Such chemistries reduce freeze-thaw damage by up to 60%, yet maintain $>90\%$ of the native permeability because the nanoparticles occupy only the roughness scale, leaving the load-bearing skeleton intact [83].

In *adsorptive filler* settings, stormwater leachate is enriched in Zn, Cu, Pb, and polycyclic aromatics. Their mitigation has moved from catch-basin treatments to *in situ* removal by the pavement itself. Biochar derived from hardwood waste ($\text{BET} \approx 600 \text{ m}^2 \text{ g}^{-1}$) and layered double hydroxides (LDHs) with flexible interlayers are the dominant sorbents. When incorporated at 5–10 wt% of the fine aggregate fraction, they introduce an internal reservoir of basic sites for anion or cation exchange without significantly altering rheology [84]. Field lysimeter trials indicate $>70\%$ reduction of dissolved Zn^{2+} after 12 months of traffic exposure. Hybrid systems, in which LDHs are immobilized on biochar scaffolds *via* sol-gel mineralization, further suppress desorption under fluctuating pH. The key design challenge is dispersion: agglomerates larger than $200 \mu\text{m}$ can block pore throats and steeply reduce hydraulic conductivity [85]. High-shear wet milling immediately before mixing has proven effective, producing a trimodal particle size distribution that aligns with the target porosity of 18–22%.

Photocatalytic pavements are intended to abate nitrogen oxides and degrade aliphatic hydrocarbons under solar irradiation. Anatase TiO_2 remains the benchmark catalyst owing to its photostability; however, its wide band gap (3.2 eV) limits activity in the visible spectrum. Two strategies have gained prominence: (i) nitrogen or carbon doping to introduce mid-gap states, extending absorption to $\sim 550 \text{ nm}$, and (ii) constructing heterojunctions with narrow-gap semiconductors such as graphitic C_3N_4 or Bi_2O_3 , which promote charge separation [86]. These composite powders are

co-precipitated with silica fume, producing 1–2 μm clusters that can be dry-blended at 3 wt% into the binder. Surface NO removal rates exceeding $45 \text{ mg m}^{-2} \text{ h}^{-1}$ have been reported under standard irradiation (0.3 W cm^{-2} , 365 nm), with <5% decline after 18 months of field aging, largely attributed to the self-cleaning action of generated hydroxyl radicals [87]. Importantly, coating rather than bulk incorporation is preferred in cementitious systems to prevent radical scavenging by calcium hydroxide; silane-anchored top layers achieve this without impeding vapor diffusion.

Integration and synergistic design. While each additive brings discrete functionality, multifunctional pavements demand synergistic integration. A promising route is the hierarchical assembly of “core-shell-matrix” composites in which (i) a porous core of recycled glass or volcanic scoria delivers structural stiffness, (ii) a mesoporous shell of biochar or LDH provides adsorption, and (iii) a surface glaze of N-doped TiO_2 supplies photocatalysis and self-cleaning [81, 87]. Such gradation confines the sacrificial chemistry to the outermost 100–200 μm , preserving the load-bearing core. Concurrently, hydrophobic silanes may be co-condensed with photocatalysts, generating amphiphobic-photocatalytic interfaces that repel oils long enough for photodegradation to occur.

Durability, environmental risk, and lifecycle considerations. Leaching and nanoparticulate release remain regulatory concerns. Long-term column studies show Ti release <1 $\mu\text{g/L}$ for well-embedded doped anatase [88], yet values escalate by an order of magnitude when dispersion is poor or the binder is highly alkaline. Encapsulation within silica fume-based geopolymer binders reduces leaching and offers a 25% lower embodied CO_2 compared with Portland cement [89]. Finally, end-of-life scenarios must be considered: pyrolytic recovery of asphalt enables retrieval and reuse of biochar-based sorbents, whereas photocatalysts are unaffected by temperatures below 400°C . Incorporation of such circularity metrics into lifecycle assessments indicates that multifunctional pavements can offset their higher upfront footprint within 5 years *via* reduced stormwater treatment and extended maintenance intervals.

In summary, the deliberate selection and spatial grading of hydrophobic, adsorptive, and photocatalytic modifiers create permeable pavements that act as active environmental reactors while retaining mechanical robustness. Future research should focus on binder-compatible dispersants, field-scale validation of synergistic core-shell architectures, and standardized protocols for nanomaterial leaching to reconcile performance gains with ecological safety.

3.4 Valorization of industrial byproducts and recycled aggregates

The integration of industrial byproducts and recycled aggregates into permeable pavement materials represents a significant stride toward both environmental sustainability and enhanced resource efficiency [90]. Given the global escalation of construction and demolition waste, as well as the increasing stringency of regulatory frameworks governing landfill and emissions, the valorization of such waste streams is both a technical imperative and an ecological necessity [91].

A variety of *industrial byproducts*, including fly ash, ground granulated blast furnace slag (GGBFS), silica fume, and steel slag, have been systematically investigated as partial or total replacements for conventional cementitious binders and aggregates. These materials offer multiple benefits: fly ash and GGBFS, owing to their latent hydraulic or pozzolanic activity, can significantly improve the workability, long-term strength, and durability of permeable concrete while also reducing the carbon footprint associated with Portland cement production [92, 93]. Silica fume, with its

ultra-fine particle size, is particularly effective in enhancing the interfacial transition zone (ITZ) and refining the pore structure, which can lead to improved mechanical performance and reduced permeability loss over time [94].

Steel slag, owing to its high angularity and strength, has been explored as a coarse aggregate alternative, contributing to the load-bearing capacity and abrasion resistance of permeable pavements [95, 96]. However, challenges remain regarding the volumetric stability and potential leaching of heavy metals, necessitating rigorous pretreatment and performance evaluation protocols.

For *recycled aggregate streams*, the incorporation of recycled concrete aggregate (RCA) and recycled asphalt pavement (RAP) has garnered considerable attention in recent years. These materials not only divert waste from landfills but also confer economic and ecological benefits [67]. RCA, characterized by higher porosity and lower density compared to natural aggregates, can enhance the infiltration capacity of permeable pavements, albeit often at the expense of compressive strength and abrasion resistance [94]. Optimizing the grading and blending ratios of RCA with natural aggregates has proven effective in balancing permeability and structural integrity.

Similarly, RAP offers unique advantages when utilized in porous asphalt mixtures, notably in terms of resource conservation and reduced demand for virgin materials. Nonetheless, the presence of aged binder and fines can influence mixture stability and clogging susceptibility, underscoring the importance of appropriate processing and quality control measures [67].

Performance trade-offs and mitigation. The principal challenges—heterogeneous composition, residual organics, and variable moisture content—are being tackled through pre-soaking protocols, CO₂-accelerated carbonation, and near-infrared (NIR) sorting for contaminant removal. 3D X-ray computed tomography now provides rapid, non-destructive quality control of pore topology, enabling data-driven adjustment of packing density in real time [90]. Life-cycle assessment (LCA) indicates that substituting 60% of virgin aggregate with construction and demolition waste (CDW) lowers embodied CO₂ by up to 35% and diverts 140 kg/m³ of waste from landfill [91], without discernible loss in infiltration capacity over a 2-year field trial.

In summary, the judicious integration of industrial by-products and recycled aggregates within permeable pavement systems holds considerable promise for advancing both the environmental and engineering objectives of sponge city infrastructure. Ongoing research is needed to further elucidate the mechanisms governing long-term performance, standardize material specifications, and foster large-scale implementation.

4. Summary

Part 1 has established the material foundations of permeable pavement systems under the Sponge City paradigm. It began by defining the hydrological, mechanical, and ecological requirements that shape design priorities, followed by a review of regulatory standards and performance criteria. The core of the chapter examined material selection and composition, covering aggregates, binders, functional additives, and the valorization of industrial byproducts and recycled aggregates. Across these sections, the emphasis has been on linking pore structure optimization with durability, sustainability, and multifunctionality.

In doing so, Part 1 highlighted how material innovation—guided by both engineering performance and circular economy principles—can reconcile permeability

with structural resilience. This material-level perspective provides the conceptual and technical groundwork for the structural design strategies, computational modeling, and multifunctional integration that will be developed in Part 2.

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Conflict of interest

The authors declare that there are no commercial or financial relationships that could be construed as a potential conflict of interest in the publication of this chapter.

Notes

This chapter is based on a synthesis of current scientific literature, experimental evidence, and engineering practice in the field of permeable pavement materials. Any opinions or interpretations expressed herein are solely those of the authors and do not necessarily reflect the views of the supporting institutions. Data availability and replication details can be provided upon reasonable request.

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References

- [1] OECD. Financial Management of Flood Risk. London, UK: IntechOpen; 2016. Available from: https://www.oecd.org/en/publications/financial-management-of-flood-risk_9789264257689-en.html [Accessed: July 15, 2025]
- [2] Nunez C, Tolliver D. What causes floods? National Geographic. 2025. Available from: <https://www.nationalgeographic.com/environment/article/floods> [Accessed: July 15, 2025]
- [3] U.S. Environmental Protection Agency. Watershed Recovery Potential Indicator Reference Sheet: Impervious Cover. 2011. Available from: https://www.epa.gov/sites/default/files/2015-10/documents/rps_impcov.pdf [Accessed: July 15, 2025]
- [4] Obara C, Fletcher C, Hable S, et al. Drainage failure and associated urban impacts under combined sea-level rise and precipitation scenarios. *Scientific Reports*. 2025;**15**:23436
- [5] Smith J. How to make our cities more spongy and less flood prone. *The Times*. 2025. Available from: <https://www.thetimes.com/life-style/property-home/article/how-to-make-our-cities-more-spongy-and-less-flood-prone-kqb69nmzb> [Accessed: July 15, 2025]
- [6] Shi C, Xia Y, Qiu H, et al. Exploring public attitudes toward implementing green infrastructure for sponge city stormwater management. *Scientific Reports*. 2025;**14**:24252
- [7] Bean E, Hunt W, Bidelspanch D. Field survey of permeable pavement surface infiltration rates. *Journal of Irrigation and Drainage Engineering*. 2007;**133**:249-255
- [8] Terraforce. 5/2024-Terracrete™ Permeable Hard Lawn Pavers Play a Vital Role in Sponge City Design. Cape Town, South Africa: Terraforce; 2024. Available from: <https://www.terraforce.com/5-2024-terracrete-permeable-hard-lawn-pavers-play-a-vital-role-in-sponge-city-design/> [Accessed: July 15, 2025]
- [9] Sustainable Technologies Evaluation Program. King City Permeable Pavement Demonstration Project: Final Monitoring and Evaluation Report. Ontario, Canada: Lake Simcoe Region Conservation Authority; 2015. Available from: https://sustainabletechnologies.ca/app/uploads/2016/02/KPP-Ext_FinalReport_Dec2015.pdf [Accessed: July 15, 2025]
- [10] U.S. Environmental Protection Agency. Stormwater Best Management Practice: Permeable Pavements. Washington, DC, USA: U.S. Environmental Protection Agency (EPA); 2021. Available from: <https://www.epa.gov/system/files/documents/2021-11/bmp-permeable-pavements.pdf> [Accessed: July 15, 2025]
- [11] US Geological Survey. Evaluating the Potential Benefits of Permeable Pavement on the State Highway Network. Upper Midwest Water Science Center; 2024. Available from: <https://www.usgs.gov/centers/upper-midwest-water-science-center/science/evaluating-potential-benefits-permeable-pavement> [Accessed: July 15, 2025]
- [12] Ahmed H, Kuva J, Punkki J. Analysing entrapped pores in concrete via x-ray computed tomography: Influence of workability and compaction time. *Construction and Building Materials*. 2024;**417**:135322
- [13] Li B, Yang Z, Zhu X, et al. Correlating microscopic pore

characteristics with permeability coefficient in porous asphalt concrete: An X-ray CT-based approach. *Road Materials and Pavement Design*. 2024;**25**:1-27

[14] Mishra A, Carrara P, Griffo M, et al. Fracture in concrete: X-ray tomography with in-situ testing, digital volume correlation and phase-field modeling. 2025. Available from SSRN: <https://ssrn.com/abstract=5170311>

[15] Huang P, Fan D, Li D, et al. Layer combination design and effect evaluation of phase change cooling asphalt pavement. *Frontiers in Materials*. 2023;**10**:1298241

[16] Pinheiro C, Landi S Jr, Lima O Jr, et al. Advancements in phase change materials in asphalt pavements for mitigation of urban heat island effect: Bibliometric analysis and systematic review. *Sustainability*. 2023;**23**:7741

[17] Salvo-Ulloa D, Indacochea-Vega I, Ossio F, et al. Critical factors for the selection of phase change materials for asphalt mixtures: A systematic review. *Cleaner Engineering and Technology*. 2025;**26**:100936

[18] Chen K, Qu F, Huang Y, et al. Advancing photocatalytic concrete technologies for design, performance and sustainable futures. *Advanced Nanocomposites*. 2024;**1**:180-200

[19] Park C, Cho M, Kim D, et al. NO_x removal of pervious concrete pavement materials with TiO₂. *Engineering Proceedings*. 2023;**36**:8

[20] Mou K, Ji X, Liu J, et al. Using piezoelectric technology to harvest energy from pavement: A review. *Journal of Traffic and Transportation Engineering*. 2025;**12**:68-86

[21] Fan W, Lei R, Dou H, et al. Sweat permeable and ultrahigh strength 3D

PVDF piezoelectric nanoyarn fabric strain sensor. *Nature Communications*. 2024;**15**:3509

[22] Zhou Y, Zhang J, Wang F, et al. Recent advances in flexible self-powered sensors in piezoelectric, triboelectric, and pyroelectric fields. *Nanoenergy Advances*. 2024;**4**:235-257

[23] United Nations Department of Economic and Social Affairs. Sustainable Development Goal 11: Make Cities Inclusive, Safe, Resilient and Sustainable. United Nations. Available from: <https://sdgs.un.org/goals/goal11>; [Accessed: July 12, 2025]

[24] The State Council of the People's Republic of China. Guideline to Promote Building Sponge Cities. Beijing, China: State Council of PRC; 2015. Available from: https://english.www.gov.cn/policies/latest_releases/2015/10/16/content_281475212984264.htm [Accessed: July 16, 2025]

[25] European Commission. Nature-Based Solutions Research Policy. Brussels, Belgium: European Commission. Available from: https://research-and-innovation.ec.europa.eu/research-area/environment/nature-based-solutions/research-policy_en [Accessed: July 16, 2025]

[26] Jin M, Lancia M, Tian Y, et al. Hydrogeological criteria to improve the sponge city strategy of China. *Frontiers in Environmental Science*. 2021;**9**:700463

[27] Minnesota Pollution Control Agency. Calculating credits for permeable pavement. Minnesota Stormwater Manual. 2022. Available from: https://stormwater.pca.state.mn.us/index.php/Calculating_credits_for_permeable_pavement [Accessed: July 16, 2025]

[28] Selbig WR, Buer N. Hydraulic, water-quality, and temperature

performance of three types of permeable pavement under high sediment loading conditions. In: U.S. Geological Survey Scientific Investigations Report, 2018-5037. Reston, Virginia, USA: U.S. Geological Survey (USGS); 2018

[29] Qiu G, Li H, Zhang Q, et al. Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. *Journal of Integrative Agriculture*. 2013;**12**:1307-1315

[30] Geldin S, Birch EL, Rodas M, et al. Assessing nature-based solution investments for urban resilience. Penn Institute for Urban Research. 2023. Available from: <https://penniur.upenn.edu/publications/assessing-nature-based-solution-investments-for-urban-resilience> [Accessed: July 16, 2025]

[31] Ministry of Housing and Urban-Rural Development of the PRC. Technical Guide for Sponge City Construction-Low Impact Development Rainwater System Construction (Trial). Beijing, China: China Construction Industry Press; 2015

[32] Ma Y, Liu X, Liu J, et al. Carbon emission accounting and reduction evaluation in Sponge City residential areas. *Water*. 2024;**16**:2535

[33] Avaungwa Terkura S, Akib S. Performance of permeable pavement systems: A review and future solutions. 2024. DOI: 10.20944/preprints202409.1150.v1

[34] Brattebo B, Booth D. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Research*. 2003;**37**:4369-4376

[35] Tian X. Application and trend analysis of Sponge Cities in alleviating urban waterlogging. In: *Proceedings of the 1st International Conference on*

Modern Logistics and Supply Chain Management (MLSCM 2024). Paris, France: Atlantis Press (part of Springer Nature); 2024. pp. 214-218

[36] Kia A. Freeze-thaw durability of air-entrained high-strength clogging resistant pervious concrete. *Construction and Building Materials*. 2023;**400**:132767

[37] California Department of Transportation (Caltrans). Pervious Pavement Design Guidance. California Department of Transportation, HQ Division of Design; 2023. Available from: <https://dot.ca.gov/-/media/dot-media/programs/design/documents/pervious-pavement-dg-dor.pdf> [Accessed: July 8, 2025]

[38] North Carolina Department of Transportation. Permeable Interlocking Concrete Pavement Guidelines. Raleigh, North Carolina, USA: NCDOT; 2024. Available from: https://connect.ncdot.gov/resources/Asset-Management/StateMaintOpsDocs/Permeable%20Interlocking%20Concrete%20Pavement%20Guidelines_March%202024.pdf [Accessed: July 11, 2025]

[39] Amani MJ, Tanzadeh R, Nejad FM, et al. Urban sustainability through pavement technologies: Reducing urban heat islands with cool pavements. *Buildings*. 2025;**15**:504

[40] Ismael SF, Alias AH, Haron NA, et al. Mitigating urban heat island effects: A review of innovative pavement technologies and integrated solutions. *Structural Durability & Health Monitoring*. 2024;**18**:525-551

[41] U.S. Department of Transportation, Federal Highway Administration. Permeable Interlocking Concrete Pavement: Tech Brief. Washington, DC, USA: FHWA, U.S. Department of Transportation; 2019. Available from:

<https://www.fhwa.dot.gov/pavement/concrete/pubs/hif19021.pdf> [Accessed: July 11, 2025]

[42] Minnesota Pollution Control Agency. Design criteria for permeable pavement. Minnesota Stormwater Manual. 2023. Available from: https://stormwater.pca.state.mn.us/index.php/Design_criteria_for_permeable_pavement [Accessed: July 16, 2025]

[43] ASTM International. ASTM C1701/C1701M-17a: Standard Test Method for Infiltration Rate of in Place Pervious Concrete. West Conshohocken, PA, USA: ASTM International; 2017. Available from: https://store.astm.org/c1701_c1701m-17a.html [Accessed: July 16, 2025]

[44] ASTM International. ASTM C1781/C1781M-21: Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems. West Conshohocken, PA, USA: ASTM International; 2021. Available from: https://store.astm.org/c1781_c1781m-21.html [Accessed: July 16, 2025]

[45] Interlocking Concrete Pavement Institute. Tech Spec 23: Maintenance Guide for Permeable Interlocking Concrete Pavements. Chantilly, VA, USA: Interlocking Concrete Pavement Institute (ICPI); 2020. Available from: <https://www.willowcreekpavingstones.com/resources/pdf/tech-spec-23-maintenance-guide-for-picp.pdf> [Accessed: July 16, 2025]

[46] Interlocking Concrete Pavement Institute (ICPI). Permeable Interlocking Concrete Pavement (PICP) Infiltration Guidelines and Testing. Chantilly, VA, USA: ICPI; 2018. Available from: <https://sek.us.com/wp-content/uploads/2018/12/PICP-Infiltration-Guidelines-and-Testing-9.18.pdf> [Accessed: July 16, 2025]

[47] European Committee for Standardization (CEN). EN 12697-19:2020 Bituminous Mixtures—Test Methods—Part 19: Permeability of Specimen. Available from: <https://standards.iteh.ai/catalog/standards/cen/e0e33c37-5f4c-4651-9281-2b73a0407f75/en-12697-19-2020> [Accessed: July 16, 2025]

[48] Stormwater Solutions. A National ASCE Standard for Permeable Interlocking Concrete Pavement. 2020. Available from: <https://www.stormwater.com/stormwater-bmps/compliance/article/21132523/a-national-asce-standard-for-permeable-interlocking-concrete-pavement> [Accessed: July 16, 2025]

[49] CEN. EN 12697-19:2012—Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 19: Permeability of Specimen. Brussels, Belgium: European Committee for Standardization (CEN); 2012. Available from: <https://standards.iteh.ai/catalog/standards/cen/5dc108d1-0ae2-4595-869a-8aaba773f764/en-12697-19-2012> [Accessed: July 15, 2025]

[50] CIRIA. The SuDS Manual (C753). London, UK: CIRIA; 2015. Available from: https://www.ciria.org/CIRIA/CIRIA/Item_Detail.aspx?iProductCode=C753 [Accessed: July 15, 2025]

[51] Asphalt Pavement Association. High RAP Asphalt Pavements: Japan Practice. Washington, DC, USA: Asphalt Pavement Association; 2023. Available from: https://www.asphaltpavement.org/uploads/documents/EngineeringPubs/IS139_High_RAP_Asphalt_Pavements_Japan_Practice-lr.pdf [Accessed: July 9, 2025]

[52] Standards Australia. AS 3996:2019 Access Covers and Grates. Available

from: <https://codehub.building.govt.nz/resources/as-39962019> [Accessed: July 16, 2025]

[53] California Concrete Pavement Industry and UC Pavement Research Center. Guidance for Permeable Interlocking Concrete Pavement (PICP) in California. Available from: <https://www.ucprc.ucdavis.edu/ccpic/pdf/2022/PICP%20Guidance%20for%20CCPIC%20%281-04-22%29.pdf> [Accessed: July 16, 2025]

[54] United States Environmental Protection Agency. Stormwater Best Management Practice: Permeable Pavements. Washington, DC, USA: U.S. Environmental Protection Agency (EPA); 2021. Available from: <https://www.epa.gov/system/files/documents/2021-11/bmp-permeable-pavements.pdf> [Accessed: July 16, 2025]

[55] Interlocking Concrete Pavement Institute. Maintenance Guide for Permeable Interlocking Concrete Pavements (Tech Spec 23). 2017. Available from: <https://www.willowcreekpavingstones.com/resources/pdf/tech-spec-23-maintenance-guide-for-picp.pdf> [Accessed: July 16, 2025]

[56] Ministry of Housing and Urban-Rural Development of the PRC. Technical Specification for Permeable Cement Concrete Pavement (CJJ/T 135-2009). 2009. Available from: <https://www.waizi.org.cn/bz/222110.html> [Accessed: July 16, 2025]

[57] Nanjing Municipal Administration for Market Regulation. Technical Specification for Permeable Pavement in Sponge City Construction (DB3201/T 1150-2023) (in Chinese). 2023. Available from: <https://amr.nanjing.gov.cn/ztl/bzhzl/tzgg/202306/P020230619600526752683.pdf> [Accessed: July 16, 2025]

[58] Ministry of Housing and Urban-Rural Development of PRC. Technical Specification for Permeable Brick Pavement (CJJ/T 188-2012) (in Chinese). 2012. Available from: <https://www.waizi.org.cn/bz/139331.html> [Accessed: July 16, 2025]

[59] Ministry of Housing and Urban-Rural Development of PRC. Technical Specification for Permeable Asphalt Pavement (CJJ/T 190-2012) (in Chinese). 2012. Available from: <https://www.waizi.org.cn/bz/139334.html> [Accessed: July 16, 2025]

[60] Beijing Municipal Commission of Planning and Natural Resources. Technical Regulations for the Design of Permeable Pavement in Beijing (DB11/T 1615-2019). 2019. Available from: <https://ghzrzyw.beijing.gov.cn/biaozhunguanli/bz/jzsj/202108/P020230801382296860824.pdf> [Accessed: July 16, 2025]

[61] British Standards Institution. Pavements Constructed with Clay, Natural Stone or Concrete Pavers. Guide for the Design of Permeable Pavements Constructed with Concrete Paving Blocks and Flags, Natural Stone Slabs and Setts and Clay Pavers (BS 7533-13:2009). 2009. Available from: <https://knowledge.bsigroup.com/products/pavements-constructed-with-clay-natural-stone-or-concrete-pavers-guide-for-the-design-of-permeable-pavements-constructed-with-concrete-paving-blocks-and-flags-natural-stone-slabs-and-setts-and-clay-pavers> [Accessed: July 16, 2025]

[62] Alvarez AE, Mahmoud E, Martin AE, et al. Stone-on-stone contact of permeable friction course mixtures. *Journal of Materials in Civil Engineering*. 2010;22:1129-1138

[63] Muhadeer Y, Liang S, Peiwen H, et al. Optimization of asphalt mixture

design based on the compressible packing model. *Frontiers in Materials*. 2023;**10**:1179114

[64] Yu F, Chu W, Zhang R, et al. Predicting the permeability and compressive strength of pervious concrete using a stacking ensemble machine learning approach. *Scientific Reports*. 2025;**15**:22506

[65] European Committee for Standardisation. EN 1097-2:2020. Tests for Mechanical and Physical Properties of Aggregates—Part 2: Methods for the Determination of Resistance to Fragmentation. Brussels, Belgium: European Committee for Standardisation (CEN); 2020. Available from: <https://cdn.standards.iteh.ai/samples/65878/64e9ecf21209497698d7794c42619f92/SIST-EN-1097-2-2020.pdf> [Accessed: July 17, 2025]

[66] ASTM International. ASTM D6928-17: Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus. 2017. Available from: <https://www.ccil.com/wp-content/uploads/2020/04/ASTM-D6928-17-Aug-2019.pdf> [Accessed: July 6, 2025]

[67] González-Martínez MÁ, Gómez-Soberón JM, Leal-Castañeda EJ. Permeable concrete with recycled aggregates. Study of its mechanical and microstructural properties. *Materials*. 2025;**18**:770

[68] Ji K, Shi C, Jiang J, et al. Determining the long-term skid resistance of steel slag asphalt mixture based on the mineral composition of aggregates. *Polymers*. 2023;**15**:807

[69] Alvarado-Vicencio RE, Garcia-Hernández A, Krebbers LT, et al. Prediction of the saturated hydraulic conductivity based on X-ray Ct analysis

of a permeable mixture bonded with a polyurethane binder. Available from SSRN 5318311

[70] Karim F, Hussain J. Assessing the asphalt binder film thickness in recycled asphalt mixtures using micro-level techniques. *Materials*. 2021;**14**:7891

[71] Park JH, Jeong ST, Bui QT, et al. Strength and permeability properties of pervious concrete containing coal bottom ash aggregates. *Materials*. 2022;**15**:7847

[72] Li G, Zhou C, Ahmad W, et al. Fly ash application as supplementary cementitious material: A review. *Materials*. 2022;**15**:2664

[73] Choi YC. The effect of colloidal nano-silica on the initial hydration of high-volume fly ash cement. *Materials*. 2025;**18**:2769

[74] Zhao H, Wang Q, Shang R, et al. Development, challenges, and applications of concrete coating technology: Exploring paths to enhance durability and standardization. *Coatings*. 2025;**15**:409

[75] Zalewski K. Pore structure influence on properties of air-entrained concrete. *Materials*. 2025;**18**:2885

[76] Woszek A, Franus W. A review of the application of zeolite materials in warm mix asphalt technologies. *Applied Sciences*. 2017;**7**:293

[77] Shu S, Zhuang C, Ren R, et al. Effect of different anti-stripping agents on the rheological properties of asphalt. *Coatings*. 2022;**12**:1895

[78] Cho H, Bae H, Park C, et al. Mechanical and microscopic characteristics of polyurethane-based pervious pavement composites. *Materials*. 2021;**14**:4365

- [79] Li J, Zhu Y, Yu J. Study on physical properties, rheological properties, and self-healing properties of epoxy resin modified asphalt. *Sustainability*. 2023;**15**:6889
- [80] Gulisano F, Jimenez-Bermejo D, Castano-Solis S, et al. Development of self-sensing asphalt pavements: Review and perspectives. *Sensors*. 2024;**24**:79
- [81] Asadi I, Jacobsen S, Baghban MH, et al. Reviewing the potential of phase change materials in concrete pavements for anti-freezing capabilities and urban heat island mitigation. *Buildings*. 2023;**13**:3072
- [82] Jin J, Miao Y, Zhao H, et al. Study on the self-healing performance of microcapsules and microcapsule-containing asphalt. *Sustainability*. 2022;**14**:12231
- [83] Kydyrbay N, Zhazitov M, Abdullah M, et al. Utilization of SiO₂ nanoparticles in developing superhydrophobic coatings for road construction: A short review. *Molecules*. 2025;**30**:2705
- [84] Fu Y, Fu X, Song W, et al. Recent progress of layered double hydroxide-based materials in wastewater treatment. *Materials*. 2023;**16**:5723
- [85] Deng H, Zhang S, Li Q, et al. Efficient removal of lead, cadmium, and zinc from water and soil by MgFe layered double hydroxide: Adsorption properties and mechanisms. *Sustainability*. 2024;**16**:11037
- [86] Kovalevskiy N, Svintsitskiy D, Cherepanova S, et al. Visible-light-active N-doped TiO₂ photocatalysts: Synthesis from TiOSO₄, characterization, and enhancement of stability via surface modification. *Nanomaterials*. 2022;**12**:4146
- [87] Kim HJ, Hong K. Evaluation of nitrogen oxide reduction performance in permeable concrete surfaces treated with a TiO₂ photocatalyst. *Materials*. 2023;**16**:5512
- [88] Facin F, Staub de Melo JV, Costa Puerari R, et al. Toxicological effects of leachates extracted from photocatalytic concrete blocks with nano-TiO₂ on daphnia magna. *Nanomaterials*. 2024;**14**:1447
- [89] Drabczyk A, Kudłacik-Kramarczyk S, Korniejenko K, et al. Review of geopolymer nanocomposites: Novel materials for sustainable development. *Materials*. 2023;**16**:3478
- [90] Azam A, Gabr A, Ezzat H, et al. Life cycle assessment and pavement performance of recycled aggregates in road construction. *Case Studies in Construction Materials*. 2024;**20**:e03062
- [91] Wang L, Shao Z, Zhang X, et al. Carbon accounting for permeable pavement based on the full life cycle approach and its application. *Sustainability*. 2024;**16**:7293
- [92] Sathe S, Dandin S. Experimental study of permeable concrete with FA and GGBS as partial replacement to cement. *European Journal of Environmental and Civil Engineering*. 2025;**29**:832-858
- [93] Yan X, Wang X, Sun C, et al. Performance analysis and admixture optimization of GBFS-HPMC/fiber pervious concrete. *Materials*. 2023;**16**:6455
- [94] Bai X, Zhou H, Bian X, et al. Compressive strength, permeability, and abrasion resistance of pervious concrete incorporating recycled aggregate. *Sustainability*. 2024;**16**:4063
- [95] Yu F, Tan S, Yin L, et al. Clogging investigation of two layered steel

slag pervious concrete incorporating
ceramsites under rainstorm. Scientific
Reports. 2025;**15**:13100

[96] Sherfenaz A, Ahmad SI,
Salauddin M. Sustainable use of
induction furnace slag as coarse
aggregate in pervious concrete: Strength
and hydrological properties. Case
Studies in Construction Materials.
2025;**22**:e04653

Design and Performance Enhancement of Permeable Pavement Materials: Material Selection, Composition, Structural Design, and Multifunctional Integration in Sponge City Applications – Part 2: Structural Design and Multifunctional Synergies: Modelling, Performance, and Future Pathways

Zhexu Xi and Xiaolin Lu

Abstract

This part advances the understanding of permeable pavements (PPs) from material composition towards structural design, multifunctionality, and predictive modeling within the Sponge City framework. The discussion first formalizes pore-structure optimization through descriptors of porosity, connectivity, tortuosity, and percolation thresholds, establishing their role in long-term infiltration and clogging resilience. Multiscale computational approaches—including continuum computational fluid dynamics (CFD), lattice Boltzmann method (LBM), network models, and coupled CFD-DEM (discrete-element method)—are synthesized with experimental validation, enabling quantitative prediction of hydraulic and mechanical performance. Structural design principles are then detailed, encompassing hierarchical layer configuration, load-transfer dynamics, freeze-thaw durability, and mechanistic-empirical criteria under saturated and cyclic traffic conditions. Maintenance strategies are evaluated through life-cycle cost (LCC) and life-cycle assessment (LCA), highlighting the superiority of preventive, data-driven interventions. Multifunctional integration is examined across thermal regulation, acoustic attenuation, and ecological co-benefits, where pore-network control and advanced additives extend performance beyond drainage. The synthesis underscores permeable pavements as adaptive, cyber-physical

systems, capable of self-sensing and multifunctional service delivery. By embedding circular material flows, multifunctional performance metrics, and digital monitoring, future pavements can operate as active urban interfaces that reconcile hydrological reliability, structural resilience, and environmental sustainability.

Keywords: permeable pavement, Sponge City, pore-structure optimization, structural and durability design, multifunctional performance, life-cycle assessment

1. Introduction

Part 2 develops the performance-driven design of permeable pavements beyond material composition towards system behavior and multifunctionality. Section 2 examines pore-structure optimization and hydraulic performance, formalizing percolation thresholds, connectivity, tortuosity, and dynamic clogging under service conditions, and introducing multiscale numerical frameworks (continuum CFD, LBM, network models, DEM, and hybrid/data-driven surrogates) with validation and uncertainty quantification. Section 3 translates these insights into structural design and durability, detailing hierarchical layer configuration, load-transfer mechanisms, freeze-thaw resistance, and mechanistic-empirical criteria under saturated and traffic-cycling states, alongside maintenance strategies and whole-life performance (LCC/LCA) optimization. Section 4 addresses multifunctional integration—including thermal regulation, acoustic attenuation, and ecological/landscape benefits—identifying material and structural levers and the trade-offs with hydraulic and mechanical reliability. The part culminates in a synthesis that positions cyber-physical, sensor-enabled, and circular-economy pathways as the route to scalable, standards-ready Sponge City deployments.

2. Pore-structure optimization and hydraulic performance

2.1 Porosity, connectivity, and percolation mechanisms

Permeable pavements derive their hydrological functionality from an engineered pore network that admits, stores, and conveys stormwater while sustaining mechanical integrity under repeated traffic loading. Three geometrical descriptors—total porosity (φ), effective connectivity (C_e), and tortuosity (τ)—govern the percolation pathways that control infiltration rate, unsaturated flow behavior, and clogging resilience.

2.1.1 Total and effective porosity

Total porosity is defined as the volumetric fraction of voids within the composite skeleton. In conventional open-graded cementitious or asphalt matrices, φ ranges from 15 to 25%—an order of magnitude higher than in dense-graded mixes. However, only the fraction of pores that are continuous to the surface contributes to hydraulic conduction. The concept of effective porosity ($\varphi_e = \varphi \times C_e$) therefore provides a more accurate predictor of field infiltration capacity. Experimental tomography of polymer-modified porous asphalt has shown that raising φ beyond $\approx 25\%$ leads to a marginal increase in φ_e because newly generated voids are frequently isolated pockets, thereby diminishing C_e and elevating τ [1]. Optimizing the aggregate size distribution to create

a bimodal structure (coarse load-bearing skeleton interlocked with a finer conducting matrix) can elevate φ_e by 10–15% without jeopardizing compressive strength.

2.1.2 Connectivity and critical percolation thresholds

Connectivity is conventionally quantified by the mean coordination number (Z) or the percolation probability $P(\varphi)$, which represents the likelihood of a pore belonging to an infinite cluster that spans the specimen thickness. Lattice Boltzmann simulations calibrated against micro-computed tomography (μ CT) datasets reveal a critical porosity $\varphi_c \approx 12\%$ for silica-polymer hybrids; below φ_c , the pore clusters are finite and infiltration ceases. Above φ_c , the hydraulic conductivity k scales as $k \propto (\varphi - \varphi_c)^n$ with an empirical exponent n between 2.0 and 3.5, echoing classic percolation theory for three-dimensional (3D) disordered media [2]. This non-linear rise implies that small porosity gains near φ_c produce disproportionately large permeability improvements—a design leverage that can be exploited via foamed asphalt technologies or gas-evolving admixtures in geopolymer binders.

2.1.3 Tortuosity and preferential pathways

Tortuosity captures the deviation of flow paths from straight lines and is inversely correlated with infiltration efficiency. High-resolution X-ray phase-contrast imaging indicates that aggregate angularity and binder film thickness jointly modulate τ ; rounded recycled glass cullet reduces τ by $\sim 12\%$ relative to crushed granite at identical φ_e , due to smoother interparticle contact and fewer dead-end pores. The resulting preferential channels exhibit local Reynolds numbers < 1 , justifying the use of Darcy-Brinkman formulations for continuum-scale modeling [3].

2.1.4 Dynamic percolation under transient clogging

Field pavements experience progressive infilling by particulates, biofilms, and calcic precipitates. Time-dependent $\varphi_e(t)$ can be captured by a logistic decay model: $\varphi_e(t) = \varphi_{e0}/[1 + \beta t]$, where β encompasses particulate load, rainfall energy, and maintenance frequency. Recent meso-scale experiments combining fluorescent tracer particles with particle-image velocimetry show that clogging initiates preferentially at pore throats of < 0.3 mm, causing a 40% drop in C_e after 24 months of simulated street dust deposition. Periodic vacuum-sweeping and pressure-washing restore $\leq 70\%$ of the initial φ_e , underscoring the interplay between pore geometry and life-cycle hydrological performance [4].

2.1.5 Design implications

Maximizing long-term infiltration therefore hinges on elevating φ_e above the percolation threshold while minimizing τ and clogging susceptibility. Practical strategies include: (i) adopting gap-graded aggregate curves targeting a uniform pore throat distribution near 1 mm; (ii) integrating fiber or polymer modifiers that stabilize the skeleton against rutting at high φ ; and (iii) embedding sacrificial calcium carbonate (CaCO_3) granules that dissolve under acidic runoff to regenerate clogged pathways [1]. Coupled hydro-mechanical models suggest that such measures can deliver a twofold increase in service-life-averaged permeability without compromising 50-year fatigue performance [3].

2.2 Numerical modeling and computational frameworks

Numerical simulation has become an indispensable complement to laboratory and field testing, allowing researchers to parse the coupled hydraulic and mechanical phenomena that govern permeable pavement performance across disparate spatial and temporal scales [5, 6]. Here, we synthesize the current state of the art, focusing on continuum-scale computational fluid dynamics (CFD), pore-scale lattice and network models, discrete-element methods (DEMs) for skeleton mechanics, and emerging hybrid and data-driven approaches.

2.2.1 Continuum CFD for macro-scale hydrodynamics

At the pavement block or parking-lot scale (10^2 – 10^4 m²), flow can be treated as a porous-medium continuum and solved with the Reynolds-averaged Navier-Stokes equations coupled to Darcy-Forchheimer drag terms. Commercial packages (e.g., FLUENT, FLOW-3D) as well as open-source solvers (OpenFOAM) routinely resolve transient rainfall events, identifying preferential flow paths, ponding hotspots, and risks of exfiltration into underlying sub-grade soils. Critical constitutive parameters—intrinsic permeability, inertial resistance coefficients, and degree of saturation—are extracted from laboratory permeametry or inverse-fitted from field inflow-outflow data [7]. Sensitivity analyses reveal that a 10-fold reduction in surface permeability, representative of moderate clogging, prolongs the time to drainage by >40% under a 50 mm h⁻¹ storm, highlighting the non-linear response to partial occlusion. Continuum CFD further enables coupling with heat-transfer modules to capture evaporative cooling and nocturnal radiative exchanges, providing first-order estimates of surface temperature mitigation under different albedo or shading scenarios [8].

2.2.2 Pore-scale lattice Boltzmann and network models

The continuum assumption breaks down in the surface course, where pores range from 0.3 to 5.0 mm and inertial effects dominate. High-resolution X-ray micro-computed tomography (μ CT) has unlocked direct numerical simulation on voxelized domains via the lattice Boltzmann method (LBM). Unlike finite-volume CFD, LBM naturally handles the tortuous, multiply connected pore topology without complex meshing and captures local Reynolds numbers exceeding 100, typical for slotted asphalts under intense runoff. Studies on asphalt rubber mixtures demonstrate that increasing connected porosity from 15 to 25% lowers hydraulic tortuosity by ~35%, boosting effective permeability while only marginally compromising compressive stiffness (< 5%) when gradation is optimized [9]. Pore-network models offer a computationally lighter alternative: pores are nodes, throats are edges, and capillary or inertial conductance laws govern flow. Stochastic realizations calibrated to μ CT images can simulate thousands of cyclic clogging-scouring sequences, elucidating percolation thresholds at which hydraulic conductivity collapses.

2.2.3 Discrete-element analysis of skeleton mechanics

Whereas fluid models probe infiltration, DEM captures the granular skeleton's mechanical integrity. Each aggregate is represented as a discrete body; contact laws—linear elastic, Hertz-Mindlin, or cohesive zone—prescribe force transmission. Numerical biaxial compression on idealized gradations shows that adding

5 wt % crumb-rubber inclusions increases energy dissipation during cyclic loading, delaying the onset of raveling. More sophisticated coupled CFD-DEM schemes solve fluid forces and particle kinematics synchronously, permitting exploration of wash-out-induced particle migration. Simulations of clogging agents (silts, tyre wear dust) reveal that particles $<75\ \mu\text{m}$ infiltrate rapidly but are retained primarily at constrictions with hydraulic radii $<0.2\ \text{mm}$; once local solid volume fraction exceeds $\sim 45\%$, drag escalates by an order of magnitude and induces uplift forces capable of destabilizing overlying aggregates—an incipient potholing mechanism corroborated by accelerated wheel-tracking tests [10].

2.2.4 Multiscale and multiphysics coupling

No single scale suffices for design. Multiscale strategies typically pass homogenized permeability and stiffness tensors upwards from μCT -derived RVE (representative volume element) simulations into pavement-level CFD/FE (finite-element) models, while stress or moisture histories feed back down to update local damage or clogging state [11]. Advances in high-performance computing allow direct coupling of LBM (pore water) with DEM (solid matrix) at domains containing $>10^7$ voxels, albeit at considerable cost; adaptive mesh refinement and graphics processing unit (GPU) acceleration now render event-scale (1–2 h) simulations tractable on institutional clusters [12, 13].

Thermo-hydro-mechanical (THM) formulations extend fidelity: latent heat of evaporation and temperature-dependent viscosity are included to predict summertime cooling efficiency, while cement hydration kinetics or asphalt aging models inform long-term modulus evolution [14]. Such THM models reproduce a 3°C diurnal amplitude reduction measured on field cells surfaced with light-colored permeable concrete relative to dense-graded controls.

2.2.5 Surrogate and data-driven modeling

To circumvent the prohibitive runtime of fully resolved CFD-DEM, surrogate models based on machine-learning regressors or reduced-order bases are gaining traction. Convolutional neural networks trained on thousands of μCT -LBM pairs predict permeability and retained-clogging mass from binary images alone, achieving $<5\%$ error on unseen geometries [15]. Physics-informed neural networks (PINNs) embed the governing equations into the loss function, capturing non-linear Forchheimer flow with fewer labeled samples [16, 17]. These surrogates enable rapid parameter sweeps: for example, a Pareto front balancing hydraulic conductivity and compressive modulus across 40,000 synthetic gradations can be mapped in minutes, guiding mix design optimization [18].

2.2.6 Model validation and uncertainty quantification

Rigorous validation remains mandatory. Benchmarking against ASTM C1701 infiltration tests, falling-head permeameters, and full-scale instrumented lysimeters constrains input ranges and reveals scale effects. Ensemble Kalman filters update model parameters in real time using embedded flowmeters, reducing predictive uncertainty by $\sim 30\%$ over a six-month monitoring period [19]. Nonetheless, knowledge gaps persist in representing biofilm growth, chemical precipitation, and freeze-thaw micro-damage. Incorporating these processes will require both novel constitutive laws and expanded experimental datasets.

Future progress hinges on tighter coupling between high-resolution experimentation and simulation. In situ μ CT capable of imaging wet pavements under load, combined with exascale computing and differentiable programming, promises truly predictive models that collapse the iteration cycle from laboratory to field deployment. As multi-objective optimization embeds hydraulic, mechanical, and environmental metrics, numerical modeling will remain the cornerstone of rational, performance-based permeable pavement design [20].

2.3 Experimental characterization and testing technologies

Permeable pavement systems impose a unique dual mandate on materials: they must sustain high traffic loads while preserving an open-pore network that guarantees rapid infiltration. Meeting these seemingly antagonistic requirements demands a multiscale suite of experimental techniques that jointly resolve pore architecture, hydraulic performance, and mechanical integrity.

2.3.1 Pore-scale imaging and quantification

X-ray μ CT now represents the gold standard for non-destructive pore analysis. Voxel resolutions down to 5 μ m permit direct measurement of total porosity, throat-size distribution, and connectivity, metrics that correlate strongly with saturated hydraulic conductivity [21]. Three-dimensional reconstructions are routinely segmented by greyscale thresholding and skeletonized to yield tortuosity and constrictivity indices. Complementary mercury intrusion porosimetry (MIP) extends the measurable pore range into the sub-micron regime, capturing the fraction of occluded pores liable to clogging [22]. While MIP sacrifices sample integrity, its pressure-intrusion profile offers rapid screening and remains invaluable for model calibration [23].

2.3.2 Hydraulic performance testing

Field-oriented falling-head and constant-head permeameters provide bulk infiltration rates under realistic boundary conditions [24]. When coupled with time-domain reflectometry probes, transient drainage curves reveal the evolution of unsaturated conductivity as a function of antecedent moisture, an essential parameter for Sponge City storm routing models. Laboratory disc infiltrometers complement these macro-scale tests, enabling high-precision flux measurements on core samples extracted from in-service pavements [24]. Across all methods, at least triplicate specimens and temperature control within $\pm 0.5^\circ\text{C}$ are recommended to ensure repeatability [25].

2.3.3 Mechanical and durability assessment

Static compressive and indirect tensile (Brazilian) tests quantify load-bearing capacity, but traffic realism demands cyclic protocols. Four-point-bending fatigue, conducted at 10 Hz to simulate rolling wheels, captures stiffness degradation and crack initiation thresholds [26]. Wheel-tracking at 60°C provides rutting susceptibility, a critical failure mode in open-graded asphalt [27]. Freeze-thaw cycling ($-20 \leftrightarrow 20^\circ\text{C}$, 300 kPa confining pressure) probes pore-water crystallization damage [28], whereas resonant column tests afford dynamic modulus spectra

relevant to seismic loads. Material loss due to abrasion is evaluated with the Cantabro drum, and results are normalized by binder content to decouple compositional effects [28].

2.3.4 Physicochemical and functional metrics

Thermal infrared thermography tracks surface temperature response under controlled irradiation to quantify heat-island mitigation potential. Acoustic impedance tubes, compliant with ISO 10534-2 [29], measure normal-incidence sound absorption across 100–2000 Hz, capturing contributions from both tortuosity and viscous damping. Sorption-desorption isotherms using ion chromatography elucidate heavy-metal immobilization [30], while accelerated ultraviolet (UV)-ozone aging chambers reveal photocatalytic self-cleaning longevity in titanium dioxide (TiO₂)-enhanced mixes [31].

2.3.5 Integrated data analytics

The high dimensionality of the datasets necessitates rigorous statistical treatment. Principal-component analysis (PCA) distinguishes coupled pore-mechanical regimes, whereas Bayesian hierarchical models reconcile laboratory fatigue life with field service records, providing probabilistic design curves [32]. Vitally, all raw image volumes and mechanical datasets should be deposited in open repositories to accelerate meta-analyses and machine-learning model development [33].

Taken together, this hierarchical testing toolbox delivers a comprehensive, reproducible portrait of permeable pavement performance, directly informing material optimization and life-cycle prediction in Sponge City infrastructure.

3. Structural design and mechanical performance

3.1 Hierarchical structural configuration and load-transfer mechanisms

Permeable pavements are conceived as multilayer, multifunctional systems in which each stratum fulfills a distinct mechanical and hydrological role. A typical cross-section—whether realized with permeable asphalt, pervious concrete, or permeable interlocking blocks—comprises (i) *Porous surface course (10–50 mm)*: Highly interconnected macro-voids (15–25%) not only deliver rapid vertical drainage, but also reduce elastic modulus relative to dense asphalt or portland cement concrete (PCC), making this layer the critical origin of tensile and shear stresses; (ii) *Permeable base or bedding layer (50–150 mm)*: Often an open-graded asphalt-treated or cement-treated permeable base that combines structural support with lateral drainage. The high-void ratio (>20%) functions as an energy dissipater, spreading wheel loads over a broader footprint while buffering stormwater; (iii) *Reservoir/sub-base layer (150–450 mm)*: A single-sized aggregate skeleton (voids $\approx$ 35–40%) stores the design water-quality volume and, owing to particle interlock, acts as the principal load-carrying course; compressive stress decays by $\geq 80\%$ within this layer under standard axle loads; (iv) *Geotextile separator*: Prevents sub-grade intrusion while permitting exfiltration; its tensile contribution is normally neglected in mechanistic design but becomes significant under weak sub-grades (California bearing ratio (CBR) < 3%); and (v) *Prepared sub-grade*: Ultimate reaction platform whose resilient modulus controls overall deflection and rutting risk.

3.1.1 Vertical and lateral stress trajectories

Under moving wheel loads, contact stresses first concentrate at the porous surface; micro-finite element imaging reveals local stress bridging around aggregate contacts before force chains descend to the base. Accelerated load testing with a one-third-scale Mobile Load Simulator confirms that increasing surface thickness from 40 to 70 mm halves the peak tensile strain at the surface-base interface, while a stiffer cement-treated base further reduces longitudinal strain by ~30% [34]. These findings corroborate the classical layered elastic solution in which vertical stress σ_z attenuates exponentially with depth ($\sigma_z \approx \sigma_0 e^{-kz}$, $k \approx 1/h_{\text{reservoir}}$ for permeable systems), the attenuation constant being governed chiefly by the modulus ratio $E_{\text{base}}/E_{\text{surface}}$.

3.1.2 Dynamic load-transfer modeling

Three-dimensional finite-element (FE) models, calibrated against full-scale heavy-vehicle tests, show that permeable pavements exhibit markedly lower shear transfer but higher compressive flexibility than their impervious counterparts. In a recent ABAQUS study, stress reductions of 70–85% were observed at 0.2 m below the surface when vehicle speed increased from 40 to 100 km h⁻¹, highlighting the velocity-dependent viscoelastic response of the porous matrix [35]. Parametric sweeps further demonstrate that a modulus gradient ($E_{\text{surface}}: E_{\text{base}}: E_{\text{reservoir}} \approx 1: 3: 5$) minimizes both rut depth and fatigue life consumption.

3.1.3 Coupled hydro-mechanical considerations

Because infiltration can transiently saturate the reservoir, the effective modulus of underlying layers may decline by up to one order of magnitude during peak storm events. Laboratory cyclic loading under controlled saturation shows a 25–40% rise in vertical total stress and commensurate strain amplification [36]. Design codes therefore prescribe a dual-safety approach: (i) hydrological sizing for a target drain-down time (commonly 24 h for rainfall of 40 mm) and (ii) mechanical sizing under the worst-case saturated resilient modulus of the sub-grade. Freeze-thaw and clogging further modulate load paths by altering void continuity; routine vacuum-sweeping is recommended once post-construction clogging reduces surface infiltration below 50 mm h⁻¹.

3.1.4 Implications for structural design

Nature-based pavement design now emphasizes hierarchical stiffness optimization rather than mere thickness addition:

- Target a surface-to-base modulus ratio ≤ 0.4 to suppress tensile strains at the critical bottom-of-surface location.
- Select reservoir aggregates with angularity index > 1.6 to maximize interlock and load diffusion without compromising void connectivity.
- Where heavy traffic (equivalent single-axle load (ESAL) $> 3 \times 10^6$) is anticipated, incorporate a thin dense-graded sacrificial layer or fiber-reinforced binder to enhance shear resistance without sealing pores.

- Employ real-time embedded strain gauges or fiber Bragg gratings at the surface-base interface to calibrate mechanistic-empirical models and trigger maintenance before rutting exceeds 8 mm.

Collectively, the hierarchical architecture and its load-transfer dynamics govern not only structural longevity but also the hydrological and thermal co-benefits that are central to the Sponge City paradigm.

3.2 Load-bearing capacity, freeze-thaw resistance, and durability design

Permeable pavements must sustain repetitive traffic loads while preserving an open-pore structure that enables infiltration; success therefore hinges on a careful reconciliation of mechanical strength with hydraulic functionality. Below, we synthesize the mechanistic principles, degradation pathways, and design strategies that underpin long-term structural reliability in cold and temperate climates.

3.2.1 Mechanistic criteria for structural adequacy

The load-bearing capacity of a permeable pavement system is governed by (i) the compressive and tensile strength of the surface course, (ii) the elastic and resilient moduli of the base and sub-base aggregates, and (iii) the confinement imparted by edge restraints and adjacent impermeable elements. Because the void ratio (typically 18–25%) reduces the effective load-bearing cross-section, laboratory-measured compressive strengths of pervious concrete or porous asphalt are commonly 40–60% lower than their dense counterparts at identical binder dosages [37]. To compensate, current mechanistic-empirical design guides adopt:

- Higher binder contents or polymer-modified binders that enhance paste stiffness without appreciably clogging pores.
- Graded aggregate skeletons (e.g., 4.75–9.5 mm for porous asphalt, 9.5–12.5 mm for pervious concrete) that develop stone-to-stone contact and minimize stress concentrations.
- Layered structural systems in which a high-permeability open-graded base (OGB) or No. 57 stone reservoir both stores runoff and spreads wheel loads onto the underlying soil.

Finite-element simulations confirm that vertical stresses dissipate rapidly within the first 150 mm of an OGB layer; thus, limiting the surface deflection to ≤ 4 mm under a standard 40-kN (kilo-Newton) axle generally ensures fatigue lives $>10^6$ load repetitions on well-compacted sub-grades ($\text{CBR} \geq 5$) [38]. Where sub-grade stiffness is marginal, geogrid reinforcement or cement-stabilized sub-base layers can further lower vertical strains by 10–15%.

3.2.2 Freeze-thaw degradation mechanisms

In cold climates, the cyclic crystallization of pore water is the principal durability threat. Two interacting mechanisms dominate: (i) hydraulic pressure, generated

when advancing ice lenses force unfrozen water through the porous network; and (ii) osmotic pressure, arising from solute concentration gradients when de-icing salts are present. Because permeable mixtures possess interconnected macropores (diameter > 0.1 mm), the critical degree of saturation (S_c) below which frost damage is negligible is relatively low ($\approx 80\%$), yet winter rain or snowmelt can maintain $S > S_c$ degree of saturation (S) for extended periods.

Experimental conditioning of pervious concrete to 300 freeze-thaw cycles at $-18^\circ\text{C}/+4^\circ\text{C}$ commonly yields:

- Mass loss of 5–12% due to raveling of loosely bonded aggregate particles.
- Reductions in dynamic modulus of 20–35%, linked to micro-cracking at the binder-aggregate interface [39].
- Declines in permeability of up to 40% as spalled paste fragments partially clog the pore structure.

Porous asphalt exhibits similar trends, though its viscoelastic mastic mitigates crack propagation at moderate sub-zero temperatures [40].

3.3 Mitigation strategies for freeze-thaw and salt attack

To enhance resistance without sacrificing infiltration, several complementary approaches have proven effective:

- Air entrainment ($\sim 5\text{--}6\%$ discrete micro-bubbles) in cementitious systems introduces pressure-relief cavities, cutting freeze-thaw mass losses by up to 50% [41].
- Supplementary cementitious materials (SCMs) such as silica fume and slag refine the paste microstructure, decreasing permeability to saline solutions while slightly raising compressive strength.
- Hydrophobic or silane surface treatments reduce capillary water uptake; field trials in Scandinavia show a twofold decrease in freeze-thaw scaling after three winters.
- Granulated rubber and polymer fibers increase fracture toughness; 0.3% polypropylene fibers, for instance, can halve surface raveling rates [42].
- Optimized winter maintenance—mechanical snow removal combined with brine application rates $< 15 \text{ g m}^{-2}$ —limits chloride ingress without compromising roadway safety.

3.4 Durability-oriented mix and structural design

A holistic durability design framework integrates material selection, structural layering, and maintenance scheduling:

- Performance-based mix design begins with target void ratios, then iteratively adjusts binder viscosity, aggregate gradation, and admixture dosage to

meet dual thresholds: permeability $\geq 2 \times 10^{-3} \text{ m s}^{-1}$ and 28-day compressive strength $\geq 20 \text{ MPa}$ for light traffic, $\geq 30 \text{ MPa}$ for heavy traffic.

- Serviceability limits are set for surface rutting ($\leq 6 \text{ mm}$ in 10 years) and fatigue cracking ($\leq 15\%$ area); mechanistic models incorporate cumulative traffic spectra and freeze-thaw damage factors derived from climatic databases.
- Life-cycle cost analysis reveals that preventive vacuum-sweeping every six months extends functional life by 5–7 years relative to passive systems [37], offsetting the added maintenance cost through deferred reconstruction.
- Probabilistic reliability assessments (e.g., Monte Carlo simulations) quantify the influence of uncertainties in sub-grade modulus, traffic growth, and clogging rates on structural performance, enabling designers to target reliability indices $\beta \geq 3.0$ ($\approx 99.9\%$ safety against structural failure).

3.4.1 Emerging avenues for durable permeable pavements

Recent research is converging on multiscale reinforcement—combining nanosilica or graphene oxide to strengthen the cementitious matrix, and macro-fibers to bridge developing cracks—and self-healing binders that re-seal micro-fractures via encapsulated rejuvenators or bacteria-induced CaCO_3 precipitation. Parallel advances in embedded acoustic emission and distributed fiber-optic sensing provide real-time damage diagnostics, allowing maintenance to transition from periodic to condition-based scheduling. Finally, coupling durability models with regional climate projections will be essential for designing pavements resilient to amplified freeze-thaw frequencies under future warming scenarios.

Collectively, these strategies illustrate that mechanical robustness and hydraulic functionality are not mutually exclusive; rather, a judicious blend of tailored materials, hierarchical structural design, and proactive maintenance can deliver permeable pavements whose service lives rival (or surpass) those of conventional dense systems, even in the most demanding freeze-thaw environments.

3.5 Maintenance strategies and whole-life performance assessment

Permeable pavements are inherently dynamic systems: hydraulic conductivity, structural integrity, and surface functionality co-evolve under the coupled influences of traffic loading, sediment ingress, freeze-thaw cycling, and chemical attack. Effective asset management therefore demands a maintenance framework that is both proactive and evidence-driven, while whole-life assessments must reconcile economic and environmental externalities across multiple decades [43, 44].

3.5.1 Preventive and corrective maintenance

Inspection data from field lysimeters and in situ falling-head tests consistently show that the critical failure mode during the first five years is pore occlusion by silt-sized particulates. Routine vacuum-sweeping at quarterly intervals—supplemented by high-pressure water flushing every 18–24 months—restores $\geq 85\%$ of the initial infiltration rate and delays costly milling operations by at least a factor of 2. Where de-icing salts are routinely applied, the regimen should integrate biannual surface

neutralization with mildly acidic rinses ($\text{pH} \approx 6.0$) to mitigate binder carbonation and salt-induced stripping. Corrective interventions, triggered when permeability falls below $\sim 0.3 \text{ cm s}^{-1}$ or rutting exceeds 10 mm, typically involve targeted core extraction and hot-in-place patching [43].

3.5.2 Performance monitoring and decision thresholds

Nature-inspired sensing architectures—embedding piezoresistive geotextiles at the base of the drainage layer—now enable continuous logging of vertical stress distribution and pore-water pressure. Coupled with low-power LoRaWAN (Long-range Wide Area Network) gateways, these sensors stream data to digital twins that forecast functional decline via Bayesian updating. We recommend three decision thresholds: (i) 10% loss of connected porosity, (ii) 30% rise in rolling resistance [45], and (iii) accumulation of ≥ 50 freeze-thaw cycles with unfavorable moisture indices [46]. Breach of any single threshold triggers a maintenance alert, while concurrent breach of two thresholds mandates immediate corrective action.

3.5.3 Life-cycle cost analysis (LCC)

Stochastic LCC models, parameterized with local unit costs and discount rates ($2\text{--}5\% \text{ yr}^{-1}$), demonstrate that a “preventive-heavy” strategy—front-loading maintenance in the first decade—minimizes the net present cost (NPC) by 8–12% relative to a reactive baseline. Sensitivity analysis identifies the cost of vacuum-sweeping and the frequency of heavy-vehicle traffic as the dominant drivers; a 20% increase in sweeping cost raises NPC by only 3%, underscoring the economic resilience of proactive upkeep [47].

3.5.4 Environmental life-cycle assessment (LCA)

Process-based LCAs, normalized to 1 m^2 of pavement over 40 years, reveal that operational energy—principally from maintenance equipment—accounts for $< 15\%$ of the global warming potential (GWP) [48]. Conversely, the avoided runoff and associated downstream treatment confer a mean credit of $-7.5 \text{ kg CO}_2\text{-eq m}^{-2}$, more than offsetting the embodied emissions of polymer-modified binders used in surface rejuvenation [24]. These findings highlight the pivotal role of permeable pavements in municipal decarbonization pathways when maintenance is optimized.

3.5.5 Integrated whole-life decision framework

To reconcile the probabilistic LCC and LCA outputs, we deploy a multi-objective optimization that minimizes the sum of normalized NPC and GWP subject to hydraulic reliability constraints (failure probability $< 5\%$). The Pareto frontier suggests an optimal maintenance interval of 90 days for vacuum-sweeping and 20 years for structural resurfacing in temperate climates; analogous optima for arid climates extend to 120 days and 25 years, respectively. Uncertainty propagation, executed via Latin Hypercube sampling, confirms that these optima are robust to $\pm 20\%$ variability in sediment loadings and traffic growth rates [49].

3.5.6 Outlook

Smart sensing, data-centric maintenance scheduling, and coupled LCC-LCA optimization collectively shift the paradigm from reactive repair to predictive stewardship. Future efforts should integrate machine-learned deterioration models with climate-adaptive design factors (e.g., projected storm intensities and de-icing practices) to further attenuate life-cycle risks and costs. In doing so, permeable pavements can reliably deliver hydrological and co-benefits promised by the Sponge City framework over their design life and beyond [48].

4. Multifunctional integration and environmental synergy

4.1 Thermal regulation and mitigation of the urban heat-island effect

The capacity of permeable pavements to moderate near-surface microclimates derives from the coupling of evaporative cooling, enhanced subsurface thermal inertia, and modified radiative properties. When rainfall or anthropogenic runoff infiltrates the interconnected pore network, the stored water acts as a latent-heat sink: sensible heat conducted from the pavement and convected from the overlying boundary layer is dissipated through evaporation at the void walls, yielding surface temperature depressions of 8–15°C under peak summer insolation in field trials across temperate and subtropical cities [50–52]. Continuous or intermittent irrigation extends the evaporative phase and has been shown to halve midday radiant fluxes relative to conventional asphalt, even after 72 h of antecedent drying [53].

4.1.1 Energy-balance considerations

Surface energy-balance modeling indicates that evaporation accounts for 45–65% of the net heat loss from a fully saturated permeable asphalt slab, with the remainder partitioned between sensible and ground heat-flux components [54]. The effective thermal diffusivity of a water-filled pore matrix is one order of magnitude higher than that of the dry counterpart, flattening diurnal surface-sub-grade gradients and delaying the afternoon temperature peak by up to 90 min [55]. Such phase-lag behavior confers secondary benefits for pavement durability, as peak thermal stresses coincide with reduced traffic volumes.

4.1.2 Material and structural levers

Three design variables dominate thermal performance:

- Hydraulic retention: Fine-graded sub-base layers or polymer-modified binders increase capillary rise and prolong evaporative cooling, but excessive fines content (< 10% voids) risks clogging and hydraulic failure.
- Albedo optimization: Incorporating high-reflectance aggregates (e.g., light-colored granites) or TiO₂-based surface coatings raises short-wave reflectivity by 0.15–0.25, lowering equilibrium surface temperatures by a further 3–5°C under clear-sky conditions [56].

- Latent-heat additives: Micro-encapsulated phase-change materials (PCMs) embedded in the binder phase buffer temperature swings during dry spells; laboratory slabs with 15% wt paraffin-PCM showed a 30% reduction in cumulative degree-hours above 45°C without compromising compressive strength [57].

Optimizing these levers demands a multi-objective framework that balances hydrological capacity, mechanical integrity, and thermal efficacy. Recent machine-learning surrogates trained on coupled CFD-heat-transfer simulations permit rapid screening of aggregate gradations and PCM loadings within realistic traffic and climate envelopes [58].

4.1.3 Urban-scale implications

Meso-scale atmospheric models incorporating pavement-level parameterizations project that replacing 25% of arterial surfaces in a compact European city with high-albedo, water-retentive permeable concrete could attenuate nocturnal urban canopy air temperatures by $0.7 \pm 0.2^\circ\text{C}$ during heat-wave episodes [59]. Such reductions are sufficient to lower peak cooling-energy demand by 3–5% and heat-stress mortality by 1–2% according to epidemiological risk curves. Co-deployment with blue-green infrastructure amplifies these benefits through synergistic evaporative sources and shading. Collectively, these advances position permeable pavements not merely as drainage devices but as active microclimatic modulators, integral to holistic urban heat-island mitigation within the Sponge City paradigm.

4.2 Noise attenuation and acoustic performance

Urban pavements contribute appreciably to environmental noise, particularly in densely populated districts where tyre-road interaction is a dominant source above engine noise at moderate to high speeds. Permeable pavements, by virtue of their interconnected pore network and compliant surface textures, offer a passive yet robust strategy for reducing road traffic noise [60, 61]. This section synthesizes the mechanistic understanding of acoustic energy dissipation in porous media, examines material and structural levers for optimizing acoustic response, and outlines state-of-the-art characterization and modeling approaches germane to permeable pavement design.

4.2.1 Physical mechanisms of noise reduction

Tyre-road noise is predominantly generated through (i) air-pumping as tread blocks enter and exit pavement cavities, (ii) stick-slip interactions between tread rubber and surface asperities, and (iii) vibration of tread elements and pavement layers [62]. Permeable pavements mitigate these mechanisms via two principal pathways: (1) acoustic absorption, where incident sound waves propagate into the pore network and are attenuated by viscous and thermal losses along pore walls; and (2) acoustic scattering and dissipation, where surface roughness and graded porosity disrupt coherent wave propagation and reduce specular reflection [60]. The aggregate-binder microstructure determines flow resistivity and tortuosity, both of which regulate the balance between energy dissipation and sound transmission. Optimal acoustic performance typically emerges when pores are sufficiently open to admit sound waves (reducing reflection) yet small and tortuous enough to maximize viscous damping [62].

4.2.2 Material selection and microstructural control

The interplay between aggregate gradation, binder viscosity, and void continuity is critical to shaping acoustic response. Coarse aggregate skeletons with controlled fines content can yield bimodal pore size distributions that enhance broadband absorption [63]. Polymer-modified binders or bio-based resins may provide a more compliant matrix, attenuating vibration-induced noise while preserving structural integrity. Incorporation of elastomeric inclusions, recycled rubber particles, or microfibrinous additives can further dampen high-frequency vibrations [64]. However, excessive fines or clogging by particulates reduces permeability and negates acoustic benefits, underscoring the necessity of designing for maintainable porosity. In situ rejuvenation techniques (e.g., vacuum-assisted unclogging or biofilm management [65]) should therefore be integrated into life-cycle planning.

4.2.3 Structural design considerations

From a structural perspective, layered configurations, such as an acoustically absorptive surface course overlain on a stiffer base, can be tuned to minimize reflective impedance mismatches. The thickness of the surface layer governs the frequency bands of dominant attenuation: thinner layers attenuate higher frequencies, whereas thicker porous lifts extend absorption into lower frequency ranges relevant to heavy vehicles. Jointing patterns, edge restraints, and subsurface drainage pathways also influence acoustic performance through their effects on continuous porosity and resonance phenomena [64, 65]. Integrative design that couples hydrological objectives with acoustic targets (e.g., specifying minimum connected porosity for both infiltration and sound absorption [66]) can produce multibenefit pavements without compromising structural safety.

4.2.4 Characterization and metrics

Quantitative evaluation of acoustic performance relies on laboratory and field protocols spanning material- and system-level scales. The normal-incidence sound absorption coefficient is obtained via impedance tube methods (e.g., ISO 10534-2 [67]), enabling rapid parametric assessment of pore-structure effects. In situ measurements (such as Close-Proximity [68] and Statistical Pass-By methods [69]) capture tyre-pavement noise under representative traffic conditions. Complementary metrics include flow resistivity, airflow resistivity gradients, and dynamic stiffness, which can be correlated with acoustic absorption spectra [70]. Advanced microtomography and image-based modeling allow direct extraction of tortuosity and pore morphology, enabling virtual prototyping of noise-optimized mixtures prior to full-scale trials [71].

4.2.5 Modeling and predictive tools

Multiphysics models integrating fluid dynamics, acoustics, and structural mechanics are increasingly used to predict frequency-dependent absorption and transmission loss. Johnson-Champoux-Allard (JCA)-type models, extended to account for non-linear flow regimes and anisotropic pore networks, can capture the key controls of porosity, viscous characteristic length, and thermal characteristic length. Coupling discrete-element methods (DEMs) or lattice Boltzmann methods

with acoustic wave propagation solvers enables simulation of tyre-pavement interactions at micro- to meso-scales. Machine-learning frameworks, trained on large databases of mix designs and acoustic outcomes, are nascent but promising tools for expediting design space exploration.

4.2.6 Trade-offs, durability, and maintenance

Acoustic gains must be balanced against mechanical durability and long-term permeability. High porosity improves sound absorption but often reduces load-bearing capacity and increases susceptibility to raveling. Freeze-thaw cycles, binder ageing, and particulate clogging progressively degrade acoustic efficacy. Thus, acoustic performance should be embedded within a whole-life assessment that includes maintenance strategies (e.g., periodic suction sweeping, water jetting) and service-life modeling. Adaptive materials—capable of self-cleaning or self-healing—present an opportunity to sustain acoustic and hydrological functions concurrently.

4.3 Ecological and landscape benefits

Permeable pavements can serve as micro-ecological infrastructure, reconnecting fragmented urban ecosystems. Beyond stormwater infiltration, their porous matrices, surface textures, and subsurface voids can be designed to support vegetation and soil life, moderate microclimates, and enrich streetscapes. We summarize key ecological and landscape benefits, focusing on design strategies that maximize multifunctionality while maintaining structural integrity [72].

4.3.1 Habitat provision and biodiversity support

The interstitial spaces within permeable concrete or asphalt, combined with engineered base layers, can create heterogeneous moisture and temperature regimes conducive to microbial consortia, mosses, and opportunistic herbaceous species [73]. When joint patterns are widened or infilled with engineered soils, they become linear “planter joints” that host pollinator-friendly flora. Such microhabitats are particularly valuable in highly sealed districts where traditional green plots are scarce [74]. Faunal use—by ground beetles, ants, and urban-adapted amphibians—has been documented where pavements interface with vegetated swales or rain gardens, indicating that permeable surfaces may serve as stepping stones that expand habitat networks [75]. Design strategies include (i) specifying fines-free aggregate bands to encourage colonization [76], (ii) integrating seed banks or mycorrhizal inoculants in bedding layers [77], and (iii) grading sub-base moisture to avoid prolonged anoxia detrimental to root respiration [78].

4.3.2 Enhancement of ecological connectivity

At the urban scale, permeable pavement corridors can link discrete green spaces, facilitating organism movement and gene flow. While their structural depth is limited relative to full bioswales, distributed patches along sidewalks and parking lots reduce the “impervious barrier effect” [79]. Embedding these pavements within a broader green-blue network—roadside tree pits, green roofs, and detention ponds—creates a mosaic that cumulatively delivers significant ecological connectivity. Modeling

approaches borrowed from landscape ecology (e.g., least-cost path analysis) can quantify the contribution of permeable segments to connectivity indices, informing prioritization and retrofitting strategies [80].

4.3.3 Microclimate regulation and urban heat-island mitigation

PPs influence surface energy balance through higher evaporative fluxes and, when vegetated, through shading and transpiration [81]. Compared with dense asphalt, surfaces with elevated albedo aggregates and moist pore networks exhibit reduced peak temperatures, attenuating nocturnal heat release. The capillarity of the sub-base can be engineered to sustain near-surface moisture for evaporative cooling during heat waves, while still draining excess stormwater [82]. Thermal simulations coupling Richards' equation for unsaturated flow with heat-transfer models reveal that even modest evaporative cooling (1–2°C surface temperature reduction) can yield perceptible thermal comfort gains for pedestrians [83]. Design trade-offs—such as balancing cooling with freeze-thaw durability—require site-specific optimization.

4.3.4 Water-quality improvement and biogeochemical functions

Vegetated or biologically active permeable systems can serve as reactive filters that attenuate nutrients, hydrocarbons, and heavy metals [84]. Biofilm growth on aggregate surfaces enhances sorption and biodegradation pathways, while engineered amendments (e.g., biochar, zeolites, TiO₂-coated sands) target specific contaminants [85]. Seasonal dynamics are critical: winter de-icing salts can suppress microbial activity, and clogging can shift flow paths, diminishing treatment efficacy [86]. Routine vacuuming and periodic media rejuvenation preserve both hydraulic and biogeochemical performance. From an ecosystem services perspective, the incremental pollutant load reductions can be monetized within total maximum daily load (TMDL) frameworks, strengthening the case for permeable pavements in watershed management plans [87].

4.3.5 Esthetic quality, social perception, and well-being

Landscape performance extends beyond biophysical metrics to encompass human experience. Textural diversity, vegetated joints, and patterned permeable pavers contribute visual interest and seasonal change, countering the monotony of conventional hardscapes [88]. Empirical studies show that streets integrating green-gray hybrids increase perceived walkability and restorative value, which can indirectly promote active transport and social interaction [89]. However, maintenance legibility is crucial: unmanaged weed growth may be interpreted as neglect, undermining public acceptance [90]. Thus, planting palettes should balance ecological function with esthetic coherence and low maintenance, guided by cues-to-care design principles [91].

4.3.6 Quantifying ecosystem services

Assigning quantitative value to ecological and landscape co-benefits remains challenging but necessary for mainstream adoption. Life-cycle assessment (LCA) coupled with ecosystem service valuation (ESV) can capture trade-offs among carbon footprint, heat mitigation, biodiversity, and hydrological benefits [92]. Indicators such as habitat suitability indices, pollinator visitation rates, surface temperature reductions, and avoided runoff volumes can be standardized for inclusion in performance

specifications [93]. Integrating sensors enables continuous monitoring of moisture, temperature, and biological activity, converting qualitative benefits into actionable datasets for adaptive management [94].

In sum, when designed as multifunctional elements, permeable pavements transcend their conventional drainage role, acting as fine-grained ecological infrastructure that reconciles urban performance with environmental quality. Their success depends on integrative design that aligns hydrological, mechanical, and ecological objectives within the broader Sponge City framework.

5. Summary

This part consolidated the system-level principles that govern permeable pavement performance:

- *Hydraulic architecture.* Effective porosity, throat-size distribution, connectivity, and tortuosity jointly control infiltration and clogging resilience. Designing above the percolation threshold while minimizing tortuosity enables durable conductivity under transient sediment loading.
- *Modeling toolbox.* Coupled CFD/Forchheimer, LBM, pore network, and DEM frameworks—augmented by multiscale upscaling and data-driven surrogates—provide predictive links between microstructure, flow, and skeleton mechanics, with validation against field infiltration and lysimeter data.
- *Structural and durability design.* Hierarchical stiffness, reservoir-based load diffusion, and moisture—/temperature-aware mechanistic-empirical sizing reconcile strength with permeability; freeze-thaw risks are mitigated via air entrainment, SCMs, hydrophobic treatments, and fiber/polymer toughening.
- *Maintenance and whole-life performance.* Preventive vacuum-sweeping, condition-based triggers, and integrated LCC/LCA favor proactive stewardship, improving reliability and lowering net present costs and embodied impacts.
- *Multifunctionality.* Evaporative cooling, high-albedo/PCM strategies, acoustic absorption via tuned porosity, and reactive fillers for pollutant abatement extend benefits beyond drainage, provided porosity is maintainable and trade-offs are quantified.

Together, these results frame permeable pavements as adaptive, cyber-physical infrastructure. The concluding section distills standardizable targets and research priorities for scalable Sponge City implementation.

6. Conclusions of the two parts

Permeable pavements have evolved from single-purpose stormwater devices into multifunctional, cyber-physical elements of Sponge City infrastructure, expected to absorb, store, and reuse a large fraction of annual precipitation while withstanding decades of mechanical and climatic stress.

A central lesson of this chapter is that hydraulic and mechanical performance are co-optimizable properties of the same porous architecture. Effective porosity, throat-size distribution, and tortuosity—shaped by gap-graded aggregates, binder chemistry, and admixture dispersion—govern both infiltration and load transfer. Multiscale models (μ CT-LBM, CFD-DEM) now resolve these couplings with micrometer fidelity, revealing critical percolation thresholds ($\phi_c \approx 12\%$) and non-linear conductivity gains near that brink. Laboratory and field data further show that clogging initiates at pore throats <0.3 mm and can halve permeability within five years if maintenance is neglected, underscoring the need to design for maintainable porosity and to institutionalize periodic rejuvenation.

Structurally, permeable pavements function as adaptive hierarchies rather than static layer stacks. Gradational stiffness, high-void reservoirs, and geotextile separators distribute loads while storing runoff; yet, saturation events, freeze-thaw cycling, and sediment intrusion dynamically alter modulus and stress paths. Mechanistic-empirical design must therefore embrace dual-safety states (hydraulic and mechanical) and be calibrated with embedded sensing to pre-empt rutting and permeability collapse.

Multifunctionality is no longer ancillary. Evaporative cooling, high-albedo surfaces, and latent-heat additives can measurably depress surface and canopy temperatures, while tailored pore morphologies and compliant binders damp tyre-road noise. Photocatalytic and adsorptive fillers remove nitrogen oxides (NO_x) and metals, transforming pavements into distributed environmental reactors. The challenge is quantitative: designers must report comparable metrics— $\text{mg m}^{-2} \text{h}^{-1}$ of nitric oxide (NO) removal, dB(A) attenuation, and degree-hours above critical temperatures—to justify trade-offs against structural integrity and hydraulic reliability.

Sustainability imperatives demand circular material streams and transparent life-cycle accounting. Recycled concrete and asphalt, steel slag, and SCMs can cut embodied carbon dioxide (CO₂) by up to a third without sacrificing permeability when gradation and pretreatment are optimized; however, leaching risks and variability require rigorous Quality Assurance/Quality Control (QA/QC) and standardized specifications. Life-cycle cost and environmental assessments consistently favor preventive, data-driven maintenance over reactive repair, reinforcing the value of early investment in access, monitoring, and modular renewal strategies.

Digitalization closes the loop. Distributed fiber-optic, piezoresistive, and capacitive sensors, coupled with Bayesian updating and machine-learning surrogates, enable real-time diagnostics of clogging, moisture, and stress states, feeding predictive twins that schedule maintenance and inform iterative mix redesign.

From this synthesis, a forward agenda crystallizes: (i) integrative THM-acoustic models validated on long-term field observatories; (ii) standardized, multifunctional performance protocols that pair hydraulic thresholds with thermal, acoustic, and pollutant-removal targets; (iii) material innovation pipelines leveraging waste-derived constituents, adaptive polymers, and nano-functional fillers within cradle-to-cradle frameworks; (iv) modular, maintainable structural typologies; and (v) cyber-physical pavement systems that self-sense, self-heal, and communicate performance to asset managers.

Ultimately, the permeable pavement of the future is not merely a passive conduit for stormwater but an active urban interface—filter, battery, thermometer, and microphone—woven into the metabolism of the Sponge City. Realizing this vision

demands disciplinary convergence: material scientists must speak the language of urban climatology; hydrologists must collaborate with data scientists; and pavement engineers must engage policymakers and citizens. Only through such convergence can we deliver pavements that are not only permeable to water, but permeable to innovation, resilience, and sustainability.

In closing, the chapter underscores a shift in paradigm—from performance measured at installation to performance managed over time. As cities grapple with climate volatility, resource constraints, and public health imperatives, permeable pavements offer a rare convergence of technical efficacy and multifunctional benefit. The task ahead is to codify this promise into robust standards, scalable solutions, and intelligent systems that endure well beyond their design life, sustaining both the hydrological balance and the broader ecological and social fabric of urban environments.

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Conflict of interest

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Notes

This chapter is based on a synthesis of current scientific literature, experimental evidence, and engineering practice in the field of permeable pavement materials. Any opinions or interpretations expressed herein are solely those of the authors and do not necessarily reflect the views of the supporting institutions. Data availability and replication details can be provided upon reasonable request.

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References

- [1] Li B, Yang Z, Zhu X, et al. Correlating microscopic pore characteristics with permeability coefficient in porous asphalt concrete: An X-ray CT-based approach. *Road Materials and Pavement Design*. 2024;**25**:1-23
- [2] Residor M, Mandal S, Voigt A, et al. Flow through porous media at the percolation transition. *Physical Review Research*. 2025;**7**:L012032
- [3] Mikhailenko P, Griffa M, Pieren R, et al. Pore space of in-situ semi-dense asphalt: A characterization by X-ray tomography. *Construction and Building Materials*. 2024;**453**:139091
- [4] Garcia A, Aboufoul M, Asamoah F, et al. Study the influence of the air void topology on porous asphalt clogging. *Construction and Building Materials*. 2019;**227**:116791
- [5] Xu M, Patruno L, de Miranda S. A pressure-velocity jump approach for the CFD modelling of permeable surfaces. *Journal of Wind Engineering and Industrial Aerodynamics*. 2023;**233**:105317
- [6] Zhao D, Xu J, Wang X, et al. Numerical study on permeability of reconstructed porous concrete based on lattice Boltzmann method. *Buildings*. 2024;**14**:1182
- [7] Xiao Q, Hu X, Li X, et al. Study on the basic mechanical properties and discrete element method simulation of permeable concrete. *Sustainability*. 2023;**15**:13310
- [8] Xie J, Zhou Z. Numerical analysis on the optimization of evaporative cooling performance for permeable pavements. *Sustainability*. 2022;**14**:4915
- [9] Ren D, Xu J, Su S, et al. Characterization of internal pore size distribution and interconnectivity for asphalt concrete with various porosity using 3D CT scanning images. *Construction and Building Materials*. 2023;**400**:132751
- [10] Liu S, Ahmadi-Senichault A, Ben-Abdelwahed A, et al. Experimental investigation and DEM-CFD analysis of Darcy–Forchheimer flows in randomly packed bed systems of wood particles. *International Journal of Heat and Mass Transfer*. 2024;**235**:126229
- [11] Homel MA, Iyer J, Semnani SJ, et al. Mesoscale model and X-ray computed micro-tomographic imaging of damage progression in ultra-high-performance concrete. *Cement and Concrete Research*. 2022;**157**:106799
- [12] Fu S, Wang L. GPU-based unresolved LBM-DEM for fast simulation of gas–solid flows. *Chemical Engineering Journal*. 2023;**465**:142898
- [13] Latt J, Coreixas C. Multi-GPU acceleration of PALABOS fluid solver using C++ standard parallelism. *arXiv preprint arXiv:2506.09242*; 2025
- [14] Dal Pont S, Durand S, Schrefler BA. A multiphase thermo-hydro-mechanical model for concrete at high temperatures—Finite element implementation and validation under LOCA load. *Nuclear Engineering and Design*. 2007;**237**:2137-2150
- [15] Zhang H, Yu H, Yuan X, et al. Permeability prediction of low-resolution porous media images using autoencoder-based convolutional neural network. *Journal of Petroleum Science and Engineering*. 2022;**208**:109589

- [16] Ko D, Ji H, Ju Y. Prediction of 3D velocity field of reticulated foams using deep learning for transport analysis. *Transport in Porous Media*. 2023;**148**:577-604
- [17] Lee J, Shin S, Kim T, et al. Physics informed neural networks for fluid flow analysis with repetitive parameter initialization. *Scientific Reports*. 2025;**15**:16740
- [18] Xiao R, Liu J, Li X, et al. Intelligent evaluation of permeability function of porous asphalt pavement based on 3D laser imaging and deep learning. *Lubricants*. 2025;**13**:291
- [19] Hendricks Franssen HJ, Kaiser HP, Kuhlmann U, et al. Operational real-time modeling with ensemble Kalman filter of variably saturated subsurface flow including stream-aquifer interaction and parameter updating. *Water Resources Research*. 2011;**47**:W02532
- [20] Mishra A, Carrara P, Griffa M et al. Fracture in Concrete: X-Ray Tomography with in-Situ Testing, Digital Volume Correlation and Phase-Field Modeling. 2025. Available at SSRN: <https://ssrn.com/abstract=5170311>
- [21] Chen A, Airey GD, Thom N, et al. Characterisation of fatigue damage in asphalt mixtures using X-ray computed tomography. *Road Materials and Pavement Design*. 2023;**24**:653-671
- [22] Zhang S, Zhou XL, Zheng KR, et al. Characterization of pore structure of hardened cement-asphalt paste by mercury intrusion porosimetry. *Advanced Materials Research*. 2014;**1004**:1589-1593
- [23] Shan J, Zhang Y, Wu S, et al. Pore characteristics of pervious concrete and their influence on permeability attributes. *Construction and Building Materials*. 2022;**327**:126874
- [24] Zhu B, Chu L, Fwa TF. Improved infiltration rate determination method for interlocking-block permeable pavements using standard ASTM test apparatus. *International Journal of Pavement Engineering*. 2024;**25**:2423216
- [25] ASTM International. ASTM C1701/ C1701M-17 – Standard Test Method for Infiltration Rate of in-Place Pervious Concrete. West Conshohocken, PA: ASTM International; 2017. Available from: <https://standards.iteh.ai/catalog/standards/astm/2ec7ca76-dc5a-4b2e-9193-a0302ceb560e/astm-c1701-c1701m-17> [Accessed: July 19, 2025]
- [26] Yang B, Xiong B, Ji Y, et al. Experimental study of the fatigue performance of open-graded asphalt mixture friction course. *Materials Research Innovations*. 2015;**19**(sup5):S5-464-S5-468
- [27] Wang X, Gu X, Ni F, et al. Rutting resistance of porous asphalt mixture under coupled conditions of high temperature and rainfall. *Construction and Building Materials*. 2018;**174**:293-301
- [28] Zhang B, Li Q, Niu X, et al. Influence of a novel hydrophobic agent on freeze-thaw resistance and microstructure of concrete. *Construction and Building Materials*. 2021;**269**:121294
- [29] International Organization for Standardization (ISO). ISO 10534-2:1998 Acoustics—determination of sound absorption coefficient and impedance in impedance tubes—Part 2: Transfer-function method. (ISO, 1998). Available from: <https://www.iso.org/standard/22851.html> [Accessed: July 13, 2025]
- [30] Zhang K, Yong F, McCarthy DT, et al. Predicting long term removal of heavy metals from porous pavements for

stormwater treatment. *Water Research*. 2018;**142**:236-245

[31] Zhang D, Zhu H, Yang Q, et al. Hydration kinetics, mechanical, and photocatalytic self-cleaning performance of permeable concrete reinforced with nano-TiO₂ hydrosol. *Construction and Building Materials*. 2025;**472**:140830

[32] Gao L, Aguiar-Moya JP, Zhang Z. Bayesian analysis of heterogeneity in modeling of pavement fatigue cracking. *Journal of Computing in Civil Engineering*. 2012;**26**:37-43

[33] Enríquez-León AJ, de Souza TD, Aragão FTS, et al. Determination of the air void content of asphalt concrete mixtures using artificial intelligence techniques to segment micro-CT images. *International Journal of Pavement Engineering*. 2022;**23**:3973-3982

[34] Yang B, Li H, Li Y, et al. Experimental investigation into permeable asphalt pavement based on small-scale accelerated testing. *Applied Sciences*. 2025;**15**:4359

[35] Siao JH, Chang TC, Wang YM. A finite element model for simulating stress responses of permeable road pavement. *Materials*. 2024;**17**:3012

[36] Xu W, Qu X, Zeng T, et al. Mechanical and permeability properties of granite under hydro-mechanical coupled triaxial cyclic loading. *Physics of Fluids*. 2025;**37**:056604

[37] Schaefer VR, Kevern JT. An Integrated Study of Pervious Concrete Mixture Design for Wearing Course Applications. Final Report DTFH61-06-H-00011 (Work Plan 10). Ames: National Concrete Pavement Technology Center, Iowa State Univ; 2011. Available from: <https://www.intrans.iastate.edu/wp-content/uploads/2018/03/>

pervious_overlay_report_w_cvr.pdf [Accessed: July 19, 2025]

[38] Li H, Jones D, Harvey J. Development of mechanistic-empirical design procedure for fully permeable pavement under heavy traffic. *Transportation Research Record*. 2012;**2305**:83-94

[39] Taheri BM, Ramezani-pour AM, Sabokpa S, et al. Experimental evaluation of freeze-thaw durability of pervious concrete. *Journal of Building Engineering*. 2021;**33**:101617

[40] Maia RS, Lu Y, Hajj R. Porous asphalt mixture performance in cold regions: Case study of Chicago. *Case Studies in Construction Materials*. 2024;**20**:e03250

[41] Federal Highway Administration. Air Entrainment and Concrete Durability. Tech Brief FHWA-HIF-17-009 (U.S). Washington, DC: Department of Transportation; 2019. Available from: <https://www.fhwa.dot.gov/pavement/pubs/hif17009.pdf> [Accessed: July 11, 2025]

[42] Ozel BF, Sakallı Ş, Gündüz Y, et al. Freeze-thaw resistance of pervious concrete produced with different aggregates and fibres. *Road Materials and Pavement Design*. 2024;**1**-23

[43] Winston RJ, Al-Rubaei AM, Blecken GT, et al. Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate—The effects of street sweeping, vacuum cleaning, high-pressure washing, and milling. *Journal of Environmental Management*. 2016;**169**:132-144

[44] U.S. Army Corps of Engineers. TechNote 11: Permeable Pavement. Whole Building Design Guide. 2017. Available from: <https://www.wbdg.org/FFC/ARMYCOE/TECHNOTE/technote11.pdf> [Accessed: July 20, 2025]

- [45] Senadheera H, Deo R, Bouazza A, et al. Electro-mechanical behaviour of graphene-based geotextiles for pavement health monitoring. *Geotextiles and Geomembranes*. 2023;**51**:303-315
- [46] Golmohammadi A, Hernando D, Van den Bergh W, et al. Advanced data-driven FBG sensor-based pavement monitoring system using multi-sensor data fusion and an unsupervised learning approach. *Measurement*. 2025;**242**:115821
- [47] Singh A, Varveri A. Quantification of lifecycle costs for porous asphalt life-extension maintenance methods under managerial uncertainties. *International Journal of Pavement Engineering*. 2024;**25**:2376221
- [48] Liu J, Li H, Wang Y, et al. Integrated life cycle assessment of permeable pavement: Model development and case study. *Transportation Research Part D: Transport and Environment*. 2020;**85**:102381
- [49] Antunes LN, Ghisi E, Severis RM. Environmental assessment of a permeable pavement system used to harvest stormwater for non-potable water uses in a building. *Science of the Total Environment*. 2020;**746**:141087
- [50] Ziarani NN, Cook MJ, Freidooni F, et al. The role of near-façade flow in wind-dominant single-sided natural ventilation for an isolated three-storey building: An LES study. *Building and Environment*. 2023;**235**:110210
- [51] Qin Y, Hiller JE. Water availability near the surface dominates the evaporation of pervious concrete. *Construction and Building Materials*. 2016;**111**:77-84
- [52] Wang J, Meng Q, Zhang L, et al. Impacts of the water absorption capability on the evaporative cooling effect of pervious paving materials. *Building and Environment*. 2019;**151**:187-197
- [53] Qin Y, Hiller JE. Understanding pavement-surface energy balance and its implications on cool pavement development. *Energy and Buildings*. 2014;**85**:389-399
- [54] Bhattacharya BK, Mallick K, Desai D, et al. A coupled ground heat flux-surface energy balance model of evaporation using thermal remote sensing observations. *Biogeosciences*. 2022;**19**:5521-5551
- [55] Ghanbarian B, Daigle H. Thermal conductivity in porous media: Percolation-based effective-medium approximation. *Water Resources Research*. 2016;**52**:295-314
- [56] Wong T, Lim E, Hasan M, et al. Effectiveness of heat-reflective asphalt pavements in mitigating urban heat islands: A systematic literature review. *Journal of Road Engineering*. 2024;**4**:399-420
- [57] Hossain MT, Shahid MA, Ali MY, et al. Fabrications, classifications, and environmental impact of PCM-incorporated textiles: Current state and future outlook. *ACS Omega*. 2023;**8**:45164-45176
- [58] D'Aquilio A, Ebrahim H, Crobu E. A surrogate CFD model using machine learning for fast design explorations of the indoor environment. In: *Building Simulation 2023*. Vol. 18. West Conshohocken, PA, USA: ASTM International, IBPSA; 2023. pp. 2138-2145
- [59] Elgendy D, Tolba O, Kamel T. The impact of increasing urban surface albedo on outdoor air and surface temperatures during summer in newly

developed areas. *Scientific Reports*. 2025;**15**:25165

[60] Rochat JL, Read DR. Effective flow resistivity of highway pavements. *The Journal of the Acoustical Society of America*. 2013;**134**:4710-4716

[61] Lai F, Huang Z, Guo F. Noise reduction characteristics of macroporous asphalt pavement based on a weighted sound pressure level sensor. *Materials*. 2021;**14**:4356

[62] Praticò FG. On the dependence of acoustic performance on pavement characteristics. *Transportation Research Part D: Transport and Environment*. 2014;**29**:79-87

[63] Bichajło L, Kołodziej K. Porous asphalt pavement for traffic noise reduction and pavement dewatering—the pollution problem. In: *E3S Web of Conferences*. Vol. 45. Geneva, Switzerland: International Organization for Standardization (ISO), EDP Sciences; 2018. p. 00114

[64] Liu M, Huang X, Xue G. Effects of double layer porous asphalt pavement of urban streets on noise reduction. *International Journal of Sustainable Built Environment*. 2016;**5**:183-196

[65] Tian B, Liu Y, Niu K, et al. Reduction of tire-pavement noise by porous concrete pavement. *Journal of Materials in Civil Engineering*. 2014;**26**:233-239

[66] Yang J, Qiu Z, Zheng C. Noise reduction effect of porous asphalt pavement based on acoustic-structure coupling model. *Environmental & Earth Sciences Research Journal*. 2021;**8**:97-102

[67] ISO 10534-2:2023. Acoustics—Determination of sound absorption coefficient and impedance in impedance

tubes—Part 2: Transfer-function method. International Organization for Standardization. 2023. Available from: <https://cdn.standards.iteh.ai/samples/81294/3a864844b77c40328e79fdd8b5c82257/ISO-10534-2-2023.pdf> [Accessed: July 21, 2025]

[68] ISO 11819-2:2017 Acoustics—Measurement of the influence of road surfaces on traffic noise—Part 2: The Close-Proximity method (CPX). International Organization for Standardization. 2017. Available from: <https://cdn.standards.iteh.ai/samples/39675/08310ebd9c1240c0928d61c577528747/ISO-11819-2-2017.pdf> [Accessed: July 25, 2025]

[69] International Organization for Standardization. ISO 11819-1:2023—Acoustics—Measurement of the influence of road surfaces on traffic noise—Part 1: Statistical pass-by method (SPB method). 2023. Available from: <https://cdn.standards.iteh.ai/samples/77371/3bb5a7d9ed574005ae1a69b0ae279b0b/ISO-11819-1-2023.pdf> [Accessed: July 20, 2025]

[70] Alber S, Ressel W, Liu P, et al. Investigation of microstructure characteristics of porous asphalt with relevance to acoustic pavement performance. *International Journal of Transportation Science and Technology*. 2018;**7**:199-207

[71] Fraunhofer Institute for Building Physics IBP. n.d..Sound Absorption in an Impedance Tube. Fraunhofer IBP. Available from: <https://www.ibp.fraunhofer.de/en/building-physics-testing/sound-absorption-impedance-tube.html> [Accessed: July 20, 2025]

[72] Pratt C, Mantle J, Schofield PA. UK research into the performance of permeable pavement, reservoir structures in controlling stormwater

discharge quantity and quality. *Water Science and Technology*. 1995;**32**:63-69

[73] Kazemi F, Beecham S, Gibbs J. Streetscape biodiversity and the role of bioretention swales in an Australian urban environment. *Landscape and Urban Planning*. 2011;**101**:139-148

[74] Alberti M, Marzluff JM, Shulenberg E, et al. Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. *Bioscience*. 2003;**53**:1169-1179

[75] Lundy L, Wade R. Integrating sciences to sustain urban ecosystem services. *Progress in Physical Geography*. 2011;**35**:653-669

[76] Collins KA, Hunt WF, Hathaway JM. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. *Journal of Hydrologic Engineering*. 2008;**13**:1146-1157

[77] Fini A, Frangi P, Amoroso G, et al. Effect of controlled inoculation with specific mycorrhizal fungi from the urban environment on growth and physiology of containerized shade tree species growing under different water regimes. *Mycorrhiza*. 2011;**21**:703-719

[78] Glaister BJ, Fletcher TD, Cook PL, et al. Interactions between design, plant growth and the treatment performance of stormwater biofilters. *Ecological Engineering*. 2017;**105**:21-31

[79] Tzoulas K, Korpela K, Venn S, et al. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landscape and Urban Planning*. 2007;**81**:167-178

[80] McRae BH, Popper K, Jones A, Schindel M, Buttrick S, Hall K, et al. *Conserving Nature's Stage: Mapping*

Omnidirectional Connectivity for Resilient Terrestrial Landscapes in the Pacific Northwest. The Nature Conservancy, Portland Oregon. 2016;**47**:1-50. Available from: <http://nature.org/resilienceNW> [Accessed: June 30, 2016]

[81] Liu Y, Li T, Yu L. Urban heat island mitigation and hydrology performance of innovative permeable pavement: A pilot-scale study. *Journal of Cleaner Production*. 2020;**244**:118938

[82] Park JH, Kim YU, Jeon J, et al. Effect of eco-friendly pervious concrete with amorphous metallic fiber on evaporative cooling performance. *Journal of Environmental Management*. 2021;**297**:113269

[83] Huang B, Wu H, Shu X, et al. Laboratory evaluation of permeability and strength of polymer-modified pervious concrete. *Construction and Building Materials*. 2010;**24**:818-823

[84] Drake JA, Bradford A, Marsalek J. Review of environmental performance of permeable pavement systems: State of the knowledge. *Water Quality Research Journal of Canada*. 2013;**48**:203-222

[85] Paus KH, Morgan J, Gulliver JS, et al. Assessment of the hydraulic and toxic metal removal capacities of bioretention cells after 2 to 8 years of service. *Water, Air, & Soil Pollution*. 2014;**225**:1803

[86] Boehm A, Bell C, Fitzgerald NJ, et al. Biochar-augmented biofilters to improve pollutant removal from stormwater—can they improve receiving water quality? *Environmental Science: Water Research & Technology*. 2020;**6**:1520-1537

[87] Borah DK, Zhang H, Zellner M, et al. Advances in total maximum daily load implementation planning by modeling best management practices

and green infrastructures. *Journal of Environmental Engineering*. 2024;**150**:03124003

[88] Southon GE, Jorgensen A, Dunnett N, et al. Biodiverse perennial meadows have aesthetic value and increase residents' perceptions of site quality in urban green-space. *Landscape and Urban Planning*. 2017;**158**:105-118

[89] Hunter RF, Cleland C, Cleary A, et al. Environmental, health, wellbeing, social and equity effects of urban green space interventions: A meta-narrative evidence synthesis. *Environment International*. 2019;**130**:104923

[90] Nassauer JI. Messy ecosystems, orderly frames. *Landscape Journal*. 1995;**14**:161-170

[91] Gobster P, Nassauer J, Daniel T, et al. The shared landscape: What does aesthetics have to do with ecology? *Landscape Ecology*. 2007;**22**:959-972

[92] UNEP. Life Cycle Initiative. Guidelines for Social Life Cycle Assessment of Products and Organizations. United Nations Environment Programme; 2020. Available from: <https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020/> [Accessed: July 14, 2025]

[93] Gómez-Baggethun E, Barton DN. Classifying and valuing ecosystem services for urban planning. *Ecological Economics*. 2013;**86**:235-245

[94] Altami SA, Salman B. Implementation of IoT-based sensor systems for smart stormwater management. *Journal of Pipeline Systems Engineering and Practice*. 2022;**13**:05022004

Section 2

Sustainable Infrastructure Development

Perspective Chapter: The Role of Machine Learning in Developing Sustainable and Resilient Interconnected Infrastructure Systems

Basem A. Alkhaleel

Abstract

As global societies struggle with increasing complexity, urbanization, and the escalating impacts of climate change, the imperative to develop sustainable and resilient interconnected critical infrastructure systems (ICISs) has never been more crucial. These systems, which encompass power, water, transportation, and communication networks, form the foundation of modern economies and social well-being. Machine learning (ML), a rapidly advancing subfield of artificial intelligence, offers revolutionary potential to address these challenges. This chapter provides a comprehensive review of current applications of ML and future trends in improving the sustainability and resilience of ICISs. It explores how ML optimizes resource usage, facilitates the integration of renewable energy, improves system robustness through predictive maintenance and anomaly detection, and optimizes restoration efforts post-disruption. Domain-specific applications in transportation, water management, and energy grids are described, along with the role of ML in innovative infrastructure planning and design. The chapter also critically examines the multifaceted challenges associated with ML implementation, including data availability and quality, cybersecurity vulnerabilities, data privacy, ethical considerations such as algorithmic bias and accountability, and the need for model interpretability and robust real-world deployment. By synthesizing current research and identifying key future directions, this chapter highlights the pivotal role of ML in shaping the next generation of intelligent, adaptive, and enduring infrastructure.

Keywords: machine learning, resilient infrastructure, sustainable development, predictive maintenance, renewable energy, critical infrastructure systems

1. Introduction

1.1 The evolving landscape of infrastructure systems

The twenty-first century is characterized by an unprecedented evolution in the complexity and scale of infrastructure systems. Rapid urbanization, with projections that more than two-thirds of the world's population will reside in urban areas by 2050, places enormous strain on existing networks and requires the development of new and more sophisticated systems [1, 2]. Moreover, technological advances are simultaneously enabling and demanding smarter infrastructure, leading to the proliferation of sensors, interconnected devices (e.g., Internet of things (IoT)), and vast data streams. This digital transformation results in highly interconnected systems where the performance and stability of an infrastructure sector such as power networks are increasingly dependent on others, such as communication and water networks [3, 4].

Critical infrastructures (CIs) such as power grids, water distribution networks, transportation systems, and telecommunication networks are fundamental to the functioning of modern society and economic prosperity [4]. Disruptions to these systems, whether due to natural disasters, technical failures, or malicious attacks, can cascade through interconnected networks, leading to significant socioeconomic losses and affecting public safety [3, 4]. The concept of interconnected critical infrastructure systems (ICISs) recognizes these intricate relationships [5]. categorized these interdependencies into four main types:

- *Physical interdependency*: Where the state of one infrastructure depends on the material output of another (e.g., a water pump requiring electricity).
- *Cyber interdependency*: Reliance on information transmitted through information and communication technology (ICT) infrastructure for control and operation.
- *Geographical interdependency*: Components of different infrastructures are co-located and thus susceptible to common localized disruptions.
- *Logical interdependency*: Interconnections arising from policy, legal, or financial frameworks.

Understanding and managing these interdependencies is essential in the contemporary landscape of infrastructure systems. **Figure 1** illustrates and summarizes the different types of interdependencies.

1.2 The imperative for sustainability and resilience

The development and operation of ICISs face a dual imperative: improving sustainability and strengthening resilience. Sustainability, in this context, refers to the design and management of infrastructure to minimize environmental impact, ensure long-term economic viability, and promote social equity [6, 7]. This aligns with global initiatives such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) [2]. Key aspects include optimizing resource consumption (energy, water, and materials), reducing greenhouse gas emissions, and integrating principles of the circular economy.

Interdependency Framework

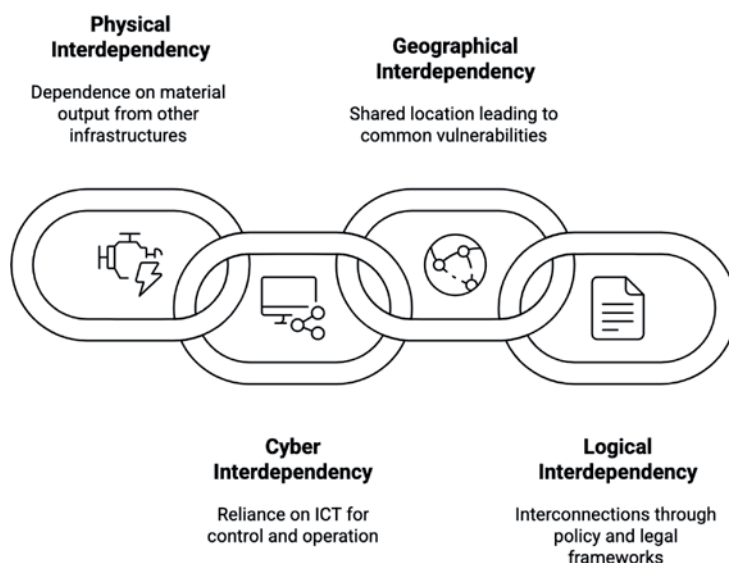


Figure 1.
 A graphical illustration of the different categories of interdependencies.

Resilience, as defined by the IEEE Task Force and in other various studies, is “the system ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event” [3, 8, 9]. This involves several dimensions, often categorized as robustness (ability to withstand stress), redundancy (availability of alternatives), resourcefulness (capacity to mobilize resources), and rapidity (speed of recovery) [1]. The challenges to achieving resilience are intensifying due to factors such as climate change (leading to more frequent and severe extreme weather events), aging infrastructure components, and the emergence of new threat vectors, including sophisticated cyberattacks targeting cyber-physical systems [3, 8].

The goals of sustainability and resilience are not mutually exclusive; in fact, they are often deeply interrelated. For example, optimizing energy efficiency in a power grid (a sustainability goal) reduces the overall load and stress on the components. Consequently, it can make the grid inherently more robust and less prone to failures during demand surges or minor disturbances, thereby improving its resilience. Similarly, efficient water management systems that minimize leaks and optimize distribution (sustainability) also conserve a critical resource, making the system more resilient to drought conditions or interruptions in supply. Machine learning (ML) offers powerful tools that can address both of these objectives, often synergistically, by enabling more intelligent and adaptive management of complex infrastructure systems.

1.3 ML: A paradigm shift for infrastructure management

ML, a branch of artificial intelligence, enables computer systems to learn from data and improve their performance on specific tasks without being explicitly

programmed for each case [4, 10]. ML algorithms identify patterns, make predictions, and inform decision-making by analyzing large and complex datasets, which are increasingly characteristic of modern ICISs. The primary categories of ML relevant to infrastructure systems include [4]:

- *Supervised learning (SL)*: This involves learning a mapping function from labeled input data (features) to known output data (labels) including:
 - *Classification*: Predicts a categorical class label. For example, classifying the operational state of an infrastructure component (e.g., normal, at-risk, failed) or predicting if a specific type of disruption will occur [8].
 - *Regression*: Predicts a continuous numerical value. Examples include forecasting energy demand, predicting the remaining useful life of a component, or estimating infrastructure restoration time after a disruption [9, 10].
- *Unsupervised learning (USL)*: This aims to find hidden patterns or intrinsic structures in unlabeled input data including:
 - *Clustering*: Groups similar data points together. In infrastructure, this can be used to identify components with similar vulnerability profiles, group consumers with similar usage patterns, or detect anomalous operational behavior [3, 10].
 - *Dimensionality reduction*: Reduces the number of features in a dataset while preserving essential information, which is useful to simplify complex models and improve computational efficiency in resilience prediction [3].
- *Reinforcement learning (RL)*: An agent learns to make a sequence of decisions by interacting with an environment. The agent receives rewards or penalties based on its actions and its goal is to learn a policy (a strategy to choose actions) that maximizes its cumulative reward over time [10]. RL is particularly suitable for dynamic optimization and control tasks in infrastructure, such as optimizing restoration schedules or controlling energy flow in smart grids [8, 11]. **Figure 2** shows the ML categories and their common subcategories and known algorithms in the ML literature.

The revolutionary potential of ML in infrastructure management lies in its ability to move beyond traditional, often reactive, approaches. By analyzing vast datasets from sensors, operational logs, weather patterns, and even social media, ML can enable proactive maintenance, optimize resource allocation in real time, predict and mitigate disruptions, and facilitate faster and more efficient recovery processes [4]. This data-driven paradigm offers a pathway to revolutionizing how ICISs are designed, built, operated, and maintained, paving the way for systems that are not only more efficient but also fundamentally more sustainable and resilient.

1.4 Chapter aims and structure

This chapter aims to provide a comprehensive review of current applications of ML in the development of sustainable and resilient interconnected infrastructure systems. Hence, it will explore the diverse methods in which ML techniques are being used to address the complex challenges faced by modern infrastructure, from

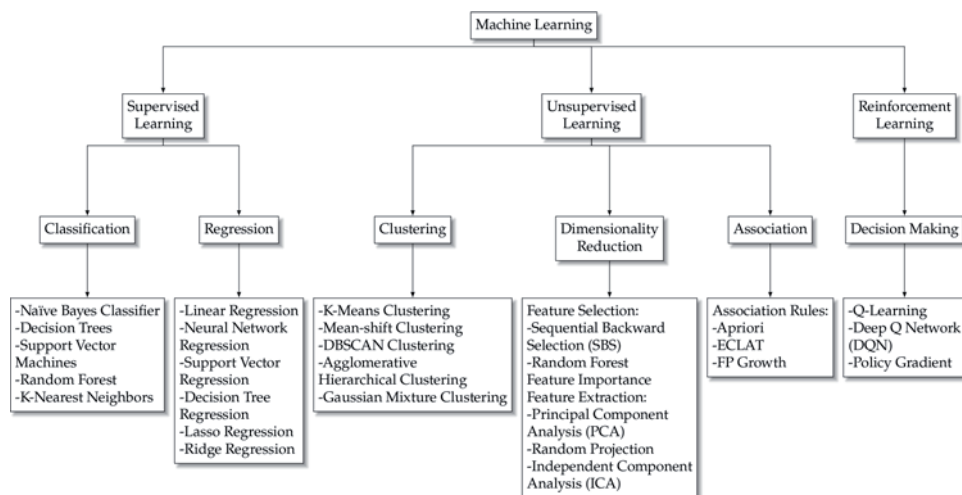


Figure 2.
 Machine learning main categories and subcategories with examples of known algorithms that fall under each subcategory (adapted from Ref. [4]).

optimizing day-to-day operations for sustainability to improving the capacity of these systems to withstand and recover from major disruptions. Furthermore, the chapter will delve into future trends and the game-changing potential of ML, while also critically examining the inherent challenges and considerations, including data issues, security, ethics, and practical deployment. The structure of this chapter is as follows:

- *Section 2* focuses on ML applications to improve sustainability in ICIS, covering resource usage optimization, energy efficiency, and integration of renewable energy sources.
- *Section 3* examines how ML contributes to improving the resilience of ICIS, including methods to improve system robustness, adaptive capacity, and optimizing post-disruption restoration and resource allocation.
- *Section 4* presents domain-specific applications of ML in key infrastructure sectors, namely transportation systems and water/wastewater management, illustrating the practical impact of these technologies.
- *Section 5* discusses the role of ML in the planning and design phases of infrastructure projects, highlighting its potential to inform urban planning and create inherently more sustainable and resilient designs.
- *Section 6* addresses the critical challenges and considerations in the implementation of ML for infrastructure systems, including data-related issues, privacy and cybersecurity concerns, ethical implications, model interpretability, and deployment hurdles.
- *Section 7* concludes the chapter by summarizing the key findings, describing emerging ML paradigms and future research directions, and reflecting on the long-term transformative potential of ML to create smarter, self-healing, and adaptive infrastructure.

Through this structured exploration, the chapter seeks to offer valuable insights for researchers, practitioners, and policymakers involved in shaping the future of critical infrastructure.

2. ML for improved sustainability in interconnected infrastructure systems

The pursuit of sustainability in interconnected infrastructure systems involves minimizing environmental footprints, optimizing resource utilization, and ensuring the long-term viability of essential services. ML offers a powerful suite of tools to achieve these objectives by enabling a more intelligent, predictive, and adaptive management of resources and energy. In the following, several examples for ML applications are illustrated.

2.1 Optimizing resource usage and energy efficiency

Efficient resource management is the cornerstone of sustainable infrastructure. ML algorithms can analyze vast amounts of data from sensors and monitoring systems to identify patterns and anomalies, leading to more informed decisions about energy consumption, water usage, and waste management. This data-driven approach can significantly reduce resource waste and greenhouse gas emissions.

2.1.1 ML for predictive analytics in energy consumption

The energy sector, particularly electricity grids, is a prime area where ML is driving sustainability. Precise forecasting of energy demand and generation is critical for efficient grid operation, minimizing the need for expensive and often carbon-intensive peak power plants, and reducing energy losses.

- *Demand forecasting:* ML models such as long short-term memory (LSTM) networks, random forests, support vector machines (SVMs), and autoregressive integrated moving average (ARIMA) models are used to predict energy demand on various scales, from individual buildings to entire regions [12]. These models can learn complex temporal patterns and incorporate exogenous variables such as weather conditions, holidays, and economic activity to improve the accuracy of forecasts [8]. Feedforward neural networks (FFNNs) have also demonstrated efficacy in predicting real-time operation costs and security margins under varying conditions [8]. The foundational concepts for these regression and classification models are detailed in works such as [10].
- *Generation forecasting:* For conventional power plants, ML can optimize generation schedules. More critically, for renewable energy sources (RES), ML is indispensable to predict their variable output (discussed further in Section 2.2).
- *Grid management and optimization:* ML-driven analytics enable smarter grid management. By predicting load profiles and potential congestion points, ML algorithms can optimize power flow, adjust transformer tap settings, and manage voltage levels, thus reducing transmission and distribution losses and improving overall grid efficiency [8, 13]. This proactive approach contrasts with

traditional reactive methods, leading to more stable and economically efficient grid operations.

The application of ML in energy consumption marks a significant shift from reactive management, where utilities respond to demand fluctuations as they occur, to proactive management. By accurately anticipating energy needs and optimizing resource allocation in advance, ML minimizes overproduction and inefficient dispatch, directly contributing to lower fuel consumption and lower emissions. This predictive capability is fundamental for integrating higher shares of variable renewable energy and improving the overall sustainability of the power sector.

2.1.2 Data-driven optimization of water usage and waste management

Similarly to the energy sector, ML is transforming water and wastewater management by enabling more efficient use of this critical resource through:

- *Leak detection and reduction:* Water loss due to leaks in aging distribution networks is a major challenge. ML algorithms, including random forests, artificial neural networks (ANNs), and convolutional neural networks (CNNs), can analyze data from flow meters, pressure sensors, and acoustic sensors to detect the presence and approximate location of leaks much faster and more accurately than traditional methods [14, 15]. Early detection and repair minimize water loss and the energy consumed in treating and pumping lost water [3].
- *Demand forecasting and optimized pumping:* ML models can predict water demand based on historical consumption patterns, weather, time of day, and special events. These forecasts allow water utilities to optimize pumping schedules, operating pumps during off-peak electricity hours or at optimal efficiency points, thus reducing energy consumption [15].
- *Wastewater treatment optimization:* ML can optimize processes in wastewater treatment plants by predicting influent characteristics and adjusting operational parameters (e.g., aeration levels and chemical dosing) in real time. This leads to reduced energy and chemical consumption while ensuring compliance with effluent standards [3].
- *Contamination source identification:* In the event of contamination in a water distribution network, ML algorithms can predict the most probable sources of contamination by analyzing sensor data, significantly speeding up response and mitigation efforts [14].
- *Smart waste management:* Beyond water, ML analyzes data from smart bins (equipped with fill-level sensors) and vehicle GPS to optimize waste collection routes, reducing fuel consumption, vehicle wear and tear, and operational costs. Predictive models can also forecast waste generation rates, helping to better plan landfill capacity and recycling facility operations. **Figure 3** illustrates the main applications of ML in water management.

The proactive nature of ML-driven resource management is evident here, as well. For example, by accurately predicting water demand, utilities can avoid unnecessary pumping or overfilling of reservoirs, saving both water and energy. Early detection

Machine Learning Applications in Water Management

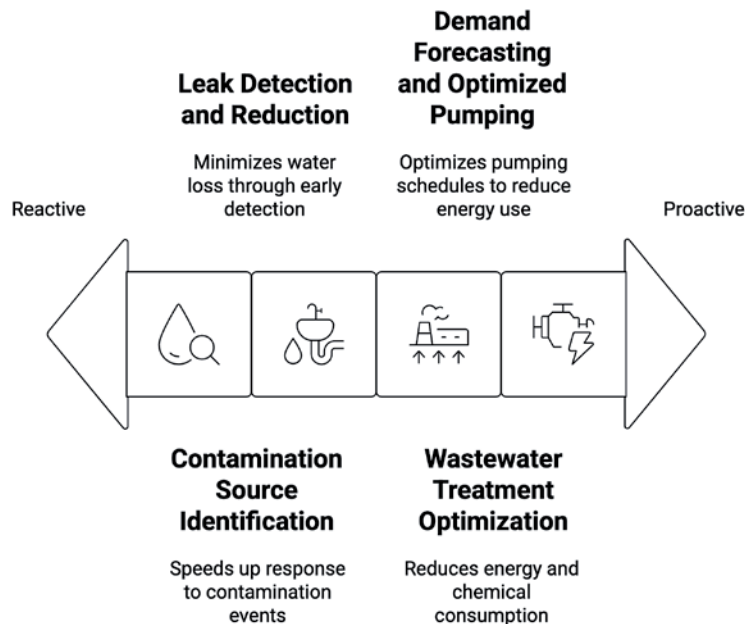


Figure 3.
A graphical illustration of ML applications in water management.

of leaks prevents prolonged water loss. This shift from fixing problems after they become significant to anticipating and preventing them is a key contribution of ML to sustainable infrastructure.

2.2 Integrating renewable energy sources (RES) into electrical grids

The transition to a sustainable energy future is highly dependent on large-scale integration of renewable energy sources, such as solar and wind power. However, the inherent intermittency and variability of these sources pose significant challenges to grid stability and reliability. ML is proving to be an indispensable technology for overcoming these challenges.

2.2.1 Forecasting intermittent renewable generation

Accurate forecasting of RES generation is fundamental for their effective integration. Grid operators need to know how much power will be available from these sources to balance supply and demand and maintain grid stability. Critical forecast models include:

- *Advanced forecasting models*: ML techniques, particularly deep learning models such as CNNs combined with LSTM networks (CNN-LSTM) and FFNNs, have shown superior performance in forecasting solar irradiance and wind speed, and consequently, power output from solar PV and wind farms [8, 12].

- *Data fusion*: These models can process various input data, including historical generation data, numerical weather predictions (temperature, cloud cover, and wind speed and direction), satellite imagery (for tracking of cloud movement), and real-time sensor data from the RES installations themselves [8].
- *Short-term and long-term forecasts*: ML provides forecasts across various time horizons, from intra-hour predictions essential for real-time dispatch to day-ahead and seasonal forecasts for operational planning and resource adequacy assessment.

2.2.2 Advanced algorithms for grid stability and load balancing with RES

With high penetration of RES, maintaining grid stability (e.g., frequency and voltage control) becomes more complex due to reduced system inertia and increased generation variability. Grid stability advanced algorithms include:

- *Dynamic control and ancillary services*: Reinforcement learning (RL) agents can be trained to learn optimal control strategies for grid assets (e.g., energy storage, flexible loads, and conventional generators) to dynamically respond to RES fluctuations and provide essential ancillary services such as frequency regulation and voltage support [8].
- *Optimal power flow (OPF)*: ML techniques can assist in solving complex OPF problems in real time, ensuring that power flows through the network efficiently and securely, even with rapidly changing RES generation profiles.
- *Congestion management*: Predictive ML models can anticipate grid congestion due to localized RES overproduction or transmission constraints, allowing operators to take preemptive actions such as re-dispatching generation or curtailing RES output when necessary.

2.2.3 Optimizing energy storage and distribution

Energy storage systems (ESS), such as batteries, are critical for mitigating RES intermittency by storing excess energy during high generation periods and releasing it during low generation or high demand periods. Applications of energy storage management include the following:

- *Optimal ESS operation*: ML algorithms can optimize ESS charging and discharge schedules based on RES generation forecasts, electricity price signals, and grid conditions to maximize RES utilization, provide grid services (e.g., peak shaving and frequency response), and improve the economic viability of storage assets [12].
- *Siting and sizing of RES and ESS*: ML can analyze geographic, meteorological, and grid data to determine optimal locations and capacities for new RES installations and ESS deployments, maximizing their effectiveness and minimizing integration costs.

The role of ML in RES integration extends beyond merely accommodating these variable sources; it is a fundamental enabler to achieve deep decarbonization of the energy sector. Traditional grid management approaches struggle with

the level of variability introduced by very high penetration of RES (e.g. > 50%). ML-powered forecasting, control, and optimization provide the necessary intelligence and adaptability to manage such complex systems. By accurately predicting the output of RES, dynamically balancing the grid, and optimizing the use of flexible resources such as energy storage, ML directly addresses the primary technical hurdles to a future energy system dominated by renewables. This capability positions ML not just as an incremental improvement, but as a foundational technology for realizing ambitious climate goals and transitioning toward a truly sustainable energy infrastructure.

3. ML for improved resilience in interconnected infrastructure systems

The resilience of interconnected infrastructure systems is essential to ensure the continuity of critical services in the face of various possible disruptions, including natural disasters, cyberattacks, pandemics, and component failures [3, 9]. Machine learning offers powerful tools to improve resilience across its various facets: improving system robustness and adaptive capacity and optimizing restoration and resource allocation efforts after a disruption has occurred. These two important aspects of resilience are discussed throughout this section.

3.1 Improving system robustness and adaptive capacity

Robustness refers to the ability of a system to withstand disturbances without significant degradation in performance, while adaptive capacity is the ability to adjust to changing conditions and recover functionality. ML contributes to these aspects primarily through predictive and real-time monitoring capabilities.

3.1.1 Predictive maintenance and failure anticipation

A key strategy for improving robustness is to prevent failures from occurring in the first place or at least mitigate their impact through early intervention. Predictive maintenance uses ML to shift from traditional time-based or reactive maintenance to condition-based and proactive strategies:

- *Data sources:* Predictive maintenance systems analyze continuous streams of data from sensors embedded in infrastructure components, measuring parameters such as vibration, temperature, pressure, flow rates, acoustic signatures, and electrical characteristics [9, 16].
- *ML models:* Regression models can be used to predict the remaining useful life (RUL) of components, allowing for planned replacement before failure. Classification algorithms (e.g., SVMs, decision trees, and neural networks) can detect patterns indicative of emerging faults or degradation [9]. For instance, studies have explored linear models, decision trees, gradient boosting, and random forests to predict network restoration times, which implicitly involves understanding component failure and repair characteristics [9].
- *Benefits:* Effective predictive maintenance reduces unexpected downtime, optimizes maintenance schedules (performing maintenance only when

needed), extends the lifespan of assets, and, importantly, can prevent minor component failures from escalating into cascading disruptions across inter-connected systems [8, 16].

3.1.2 Real-time monitoring and anomaly detection

Continuous monitoring coupled with ML-driven anomaly detection provides early warnings of deviations from normal operational states, which might indicate impending failures, ongoing attacks, or unusual system stress:

- *Learning normal behavior*: ML algorithms, including clustering techniques (e.g., K-means and DBSCAN [3]), autoencoders, and time-series models, can learn the baseline operational behavior of complex ICISs from historical data.
- *Identifying anomalies*: Once the normal behavior is modeled, these systems can identify significant deviations or anomalies in real-time sensor data or operational logs. Such anomalies could indicate equipment failure, cyber intrusions, or unexpected load patterns [8, 17]. Hidden Markov models (HMMs) have been proposed for analyzing malevolent events and determining system states under attack by modeling relationships between data streams from network nodes [4, 18]. Fuzzy logic-based clustering has also been explored to manage criticality by identifying unusual interdependency patterns [19].
- *Cyber-physical security*: In the context of cyber-physical systems, anomaly detection is critical to identify malicious activities that might target control systems or manipulate sensor readings to cause physical damage or disruption.

3.1.3 Rapid damage assessment and response post-disaster

Following a large-scale disruptive event, such as an earthquake or hurricane, a rapid and accurate assessment of damage is critical to prioritize response and recovery efforts. Different ML tools can serve this purpose:

- *Multi-source data fusion*: ML algorithms can process and fuse data from various sources, including satellite imagery, aerial photographs from drones, social media feeds, reports from first responders, and data from IoT sensor networks, to create a comprehensive picture of the affected areas [4].
- *Automated damage detection*: CNNs and other image processing techniques can automatically identify damaged buildings, blocked roads, downed power lines, and flooded areas from visual data, significantly speeding up the assessment process compared to manual approaches.
- *Internet of people (IoP)*: Social media platforms become valuable sources of real-time information during disasters. ML techniques such as natural language processing (NLP), sentiment analysis, and text mining can analyze posts, tweets, and images shared by the public to identify damage locations, calls for help, and the status of critical services [4, 20, 21]. The “Internet of People” acts as a distributed human sensor network, providing granular, on-the-ground situational awareness [22].

3.1.4 Advanced models for efficient recovery modeling

Understanding how interdependent systems recover is key to improving resilience. Novel ML approaches are being developed to model these complex dynamics more efficiently:

- *Deep operator networks (DeepONets)*: These are emerging ML architectures designed to learn mathematical operators from data. They have shown promise in accelerating the recovery modeling of interdependent systems, which could require less training data than traditional neural networks [23]. DeepONets typically consist of a “branch” network that processes input functions (e.g., individual system recovery curves) and a “trunk” network that processes output locations (e.g., time points), combining their outputs to approximate the operator [23].
- *Network topology and vulnerability*: Deep learning models, such as CNNs, can identify network topology attributes (e.g., scale-free and small world) from adjacency matrices. This classification informs the vulnerability analysis of ICISs to different failure scenarios and coupling modes, providing insights into how structural characteristics influence failure propagation and overall resilience [17].

A fundamental shift enabled by these ML applications is the move from component-level resilience strategies (e.g., hardening individual assets) to a more holistic, system-level understanding of resilience. Traditional approaches often struggled to account for complex interdependencies within ICISs, where failure of a seemingly minor component in one system could trigger a cascade of failures across others [1, 6]. ML techniques, particularly those incorporating graph theory, network science [17], and explicit modeling of interdependencies [3, 6, 23], allow for the simulation and prediction of these cascading effects. This system-aware perspective enables the development of resilience strategies that prioritize interventions based on their overall impact on the functionality of the interconnected network. For example, protecting or rapidly restoring a less critical component that provides essential support to a highly critical component in an interdependent system might yield greater overall resilience benefits than simply focusing on the critical component in isolation. This systemic perspective is vital for managing the complex adaptive nature of modern ICISs and to prevent widespread, debilitating disruptions [1].

3.2 Post-disruption restoration optimization and resource allocation

When inevitable disruptions occur, the speed and efficiency of restoration are critical determinants of overall system resilience. ML is increasingly used to optimize complex restoration processes, especially when resources are limited and multiple, often conflicting, objectives need to be balanced.

3.2.1 Multiobjective optimization for restoration

Restoration planning for ICISs is inherently a multiobjective problem, often involving trade-offs between minimizing economic costs, reducing social impacts (e.g., service disruption to vulnerable populations), and limiting environmental damage from restoration activities [6]:

- *Modeling interdependencies*: Effective restoration has to account for geospatial and functional interdependencies. For example, a damaged road might prevent access to a failed power substation, or a power outage might disable water pumps [6].
- *Learn-to-decompose (LTD) framework*: For large-scale networks, traditional optimization methods can be computationally intractable. The LTD framework, proposed by [6], combines a multiobjective evolutionary algorithm based on decomposition (MOEA/D) with a Gaussian process regression (GPR) learning module. The GPR learns characteristics of the Pareto front (the set of optimal trade-off solutions) to guide the MOEA/D search more effectively, improving convergence and solution quality for complex restoration problems involving thousands of nodes and arcs.

3.2.2 Reinforcement learning for dynamic restoration scheduling

The post-disaster environment is often dynamic and uncertain. RL offers a powerful paradigm for learning adaptive restoration strategies:

- *Sequential decision-making*: RL frames restoration as a sequential decision-making problem, where an agent (e.g., a central controller or distributed repair crews) learns an optimal policy for selecting which components to repair next, given the current state of the system and the availability of resources [11, 24]. **Figure 4** shows the main steps in developing an RL model for CI restoration.

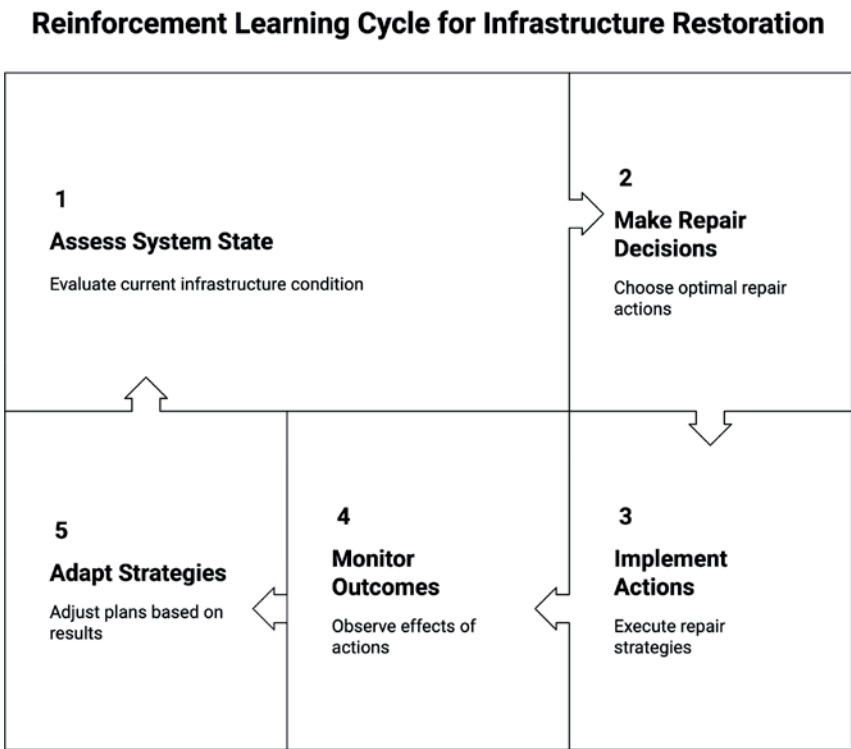


Figure 4.
A graphical illustration of RL cycle for CI restoration.

- *Deep Q-learning or deep Q network (DQN) and multi-agent DRL (MADRL):* Deep RL methods such as DQN, which use neural networks to approximate the optimal action-value function, and MADRL, which coordinates multiple learning agents, are being applied to complex restoration tasks. These include scheduling repair crews, reconfiguring networks, and dispatching mobile resources (e.g., mobile generators or water tankers) [4, 8]. The goal is typically to maximize a resilience metric, such as minimizing the area under the performance degradation curve [24].
- *Adaptive strategies:* RL agents can learn strategies that adapt to unforeseen circumstances and changing priorities during the recovery process, making them more robust than pre-planned static schedules.

3.2.3 Clustering and dimensionality reduction for efficient resource management

In large-scale ICISs, managing the vast number of components during a crisis can be overwhelming. Unsupervised ML techniques can simplify this complexity:

- *Component grouping:* Clustering algorithms (e.g., K-means, DBSCAN, and fuzzy c-means) can group infrastructure components based on their vulnerability characteristics, topological importance, or expected repair times [3, 19]. This allows for the development of targeted restoration strategies for different groups of components.
- *Dimensionality reduction:* Techniques such as principal component analysis (PCA) can reduce the number of features (characteristics) needed to describe the state of the infrastructure or the impact of a disruption, making resilience prediction models more efficient and easier to train [3]. For example, [3] demonstrated how clustering based on topological and functional features can reduce dimensionality in simulation-based ML models for infrastructure resilience prediction, improving model accuracy.
- *Fuzzy logic for criticality:* Fuzzy logic-based clustering approaches can incorporate imprecise or uncertain information about component criticality and inter-dependency strength, leading to more nuanced and realistic prioritization for restoration [19]. These methods often involve defining fuzzy inference systems with rules that map component attributes (such as number of links and type of dependency) to a degree of dependency or criticality.

The application of ML in restoration planning effectively merges the traditional distinction between purely reactive post-disaster responses and proactive pre-disaster preparedness. By learning from historical disruption data and extensive simulation scenarios, ML models can identify critical components whose failure would disproportionately complicate or prolong restoration efforts [3, 9]. This predictive insight allows decision-makers to proactively fortify these key elements or to pre-position resources based on the most likely bottlenecks that will emerge during a recovery phase [6]. This creates a feedback loop where lessons learned (via ML) from simulated or actual post-disaster scenarios directly inform and refine pre-disaster planning and investment. This evolution from simple reactive repair toward an adaptive resilience framework signifies a more mature and intelligent approach

to infrastructure management, aiming to build systems that are not only quick to recover but also learn to anticipate and mitigate future impacts more effectively.

4. Domain-specific applications of ML

Although the principles of applying ML for sustainability and resilience are broadly applicable, their specific implementations and impacts are often best understood within particular infrastructure domains. This section explores key applications in transportation systems and water/wastewater management, highlighting how ML addresses unique sectoral challenges.

4.1 Transportation systems

Transportation networks are vital for economic activity and social mobility. ML is being used to improve their efficiency, sustainability, and resilience.

4.1.1 Traffic flow optimization and congestion management

Congestion is a major issue in urban transportation, leading to wasted fuel, increased emissions, and lost productivity. ML can play a vital role in reducing the adverse effects of such an issue through:

- *Real-time traffic prediction and control:* ML algorithms, including deep learning models (e.g., long short-term memory networks (LSTMs) and graph neural networks (GNNs)) and reinforcement learning, analyze real-time data from various sources such as road sensors, GPS devices in vehicles, traffic cameras, and mobile applications [3, 6]. These models can predict traffic flow, identify emerging congestion hotspots, and dynamically optimize traffic signal timings to smooth the flow and reduce delays.
- *Intelligent route guidance:* ML-powered navigation systems can provide drivers with optimal route suggestions in real time that account for current and predicted traffic conditions, road closures, and incidents, helping to distribute traffic more evenly across the network.
- *Demand management:* ML can help predict travel demand and inform strategies such as dynamic road pricing or incentives for off-peak travel to manage congestion proactively.

4.1.2 Predictive maintenance for transportation networks

Ensuring the structural integrity and operational availability of transportation assets such as roads, bridges, tunnels, and rails is critical for safety and efficiency. Several ML tools can be utilized for this purpose:

- *Automated condition assessment:* ML algorithms, particularly computer vision techniques such as CNNs, can analyze images and sensor data (e.g., from drones, specialized vehicles, or embedded sensors) to automatically detect defects such as cracks in pavement (potholes), corrosion on bridges, or wear on railway tracks [16, 25].

- *Failure prediction and RUL estimation:* By analyzing historical maintenance records and real-time condition data, ML models can predict the likelihood of component failure and estimate the remaining useful life of assets. This enables proactive maintenance scheduling, optimizing resource allocation, and preventing costly emergency repairs and service disruptions [25]. For example, artificial intelligence (AI) algorithms have been tested to predict the degree to which reclaimed material asphalt pavements withstand moisture, a key factor in durability [25].

4.1.3 Improving resilience of transportation infrastructure

Transportation networks are highly vulnerable to disruptions from natural disasters, accidents, and security threats. Therefore, the use of ML tools can mitigate the impact of such incidents and accelerate the restoration process through several methods:

- *Impact assessment and recovery optimization:* ML models can assess the impact of disruptive events on network connectivity and capacity. For example, after an earthquake or flood, ML can quickly identify impassable routes and damaged infrastructure. This information is fed into optimization algorithms, often supported by ML, to plan efficient detour routes and prioritize repair and restoration activities [4, 6].
- *Social media for situational awareness:* As discussed previously, ML analysis of social media data (IoP) can provide valuable real-time insights into the condition of road networks during and after disasters, identifying blockages, traffic jams, and areas that need immediate help [4, 20].
- *Optimized evacuation routes:* In disaster scenarios, AI can identify optimized evacuation routes tailored to various conditions, ensuring efficiency and safety for affected populations [25].

4.2 Water and wastewater management

Sustainable and resilient water infrastructure is essential for public health, environmental protection, and economic development. ML plays an increasingly important role in optimizing water and wastewater systems by improving water treatment operations, detecting water leaks in such systems, and improving resilience in water distribution systems.

4.2.1 Optimizing treatment plant operations

Water and wastewater treatment plants (WWTPs) are complex facilities with significant energy and chemical consumption. Different roles of ML can take place in such facilities:

- *Process control and efficiency:* ML algorithms can analyze real-time sensor data (e.g., flow rates and water quality parameters such as turbidity, pH, and nutrient levels) and operational data to optimize treatment processes. This includes adjusting aeration levels in biological treatment, optimizing

chemical doses for disinfection or coagulation, and managing sludge processing to reduce energy consumption and chemical usage while maintaining effluent quality standards [3, 14, 15].

- *Predictive control*: ML can predict influent characteristics (e.g., pollutant loads) based on upstream conditions or rainfall events, allowing plant operators to proactively adjust treatment processes to handle variations effectively.

4.2.2 Leak detection and infrastructure integrity

Non-revenue water (NRW) due to leaks is a major issue for water utilities worldwide, leading to significant water and energy losses. This issue can be handled through ML tools:

- *Smart metering and anomaly detection*: The deployment of smart water meters provides granular consumption data. ML algorithms can analyze these high-frequency readings, together with data from network sensors (flow, pressure, and acoustic), to detect anomalies that indicate leaks or pipe bursts much earlier and more accurately than traditional methods [3, 14, 15].
- *Localization of leaks*: Advanced ML models can help pinpoint the location of leaks by correlating sensor readings and understanding hydraulic network behavior, allowing faster repair and minimizing water loss.
- *Pipe failure prediction*: By analyzing historical data on pipe material, age, soil conditions, pressure fluctuations, and past failures, ML can predict the likelihood of future pipe failures, allowing utilities to prioritize pipe replacement and rehabilitation programs.

4.2.3 Improving efficiency and resilience in water distribution

Ensuring a reliable and efficient supply of clean water to consumers is a primary goal of the water distribution network with significant impact on society. Several ML models can help achieving this goal:

- *Demand forecasting*: ML models accurately forecast water demand on various temporal and spatial scales, considering factors such as weather, seasonality, day of the week, and special events. This enables better planning of water production, storage, and distribution [15].
- *Optimized pump operations and pressure management*: Based on demand forecasts and real-time network conditions, ML can optimize pump schedules to minimize energy consumption (e.g., pumping during periods of off-peak electricity tariff) and manage pressure within the distribution network to reduce pipe stress and minimize leakage [3, 6].
- *Resilience modeling*: Clustering of components in water networks based on their topological and functional characteristics, as demonstrated by [3], can improve the accuracy of resilience prediction models and inform restoration strategies after disruptions.

A notable aspect emerging from the application of ML across these diverse infrastructure domains is the potential for cross-domain learning and the transferability of models and techniques. Many fundamental ML tasks, such as time-series forecasting, anomaly detection, classification for fault diagnosis, and optimization for resource allocation, are common requirements across sectors such as energy, water, and transportation [3, 6, 8, 12–16, 25]. For example, the principles of predictive maintenance, which involve learning degradation patterns from sensor data, are conceptually similar whether applied to power transformers, water pipelines, or bridge structures. The core ML algorithms, such as those described in foundational texts such as [10] (e.g., regression, decision trees, and neural networks), are often data-agnostic in their mathematical foundations. This inherent similarity suggests that best practices, successful model architectures, feature engineering techniques, and even pre-trained model components (which can be fine-tuned for specific applications) could potentially be shared or adapted across different infrastructure sectors. This transferability can significantly accelerate the innovation cycle, reduce development costs, and prevent “reinvention of the wheel” in each domain. Recognizing and fostering this potential for cross-domain learning can encourage more collaborative research initiatives and a more unified approach to leverage ML for the holistic improvement of all interconnected critical infrastructures, ensuring that advancements in one area can quickly benefit others.

5. ML in infrastructure planning and design

The planning and design phases of infrastructure projects lay the foundation for their long-term sustainability and resilience. Decisions made in these early stages have profound and lasting impacts on resource consumption, environmental footprint, operational efficiency, and vulnerability to disruptions. ML is emerging as a powerful tool for advising these critical decisions, enabling more data-driven, predictive, and optimized approaches to infrastructure development.

5.1 Informed urban planning through data analytics

Urban planning involves complex decision-making processes that must consider a multitude of interacting factors. ML can help planners make better informed decisions by extracting insights from large, heterogeneous datasets:

- *Analyzing spatio-temporal dynamics:* ML algorithms can analyze historical and real-time data on population distribution, demographic trends, land use patterns, transportation flows, economic activities, and environmental conditions to understand the current state and predict future urban development trajectories [6, 7, 16, 25].
- *Predicting infrastructure demand:* By modeling urban growth scenarios, ML can forecast the future demand for various infrastructure services, such as energy, water, transportation, and housing. This helps identify potential stress points and capacity shortfalls in existing infrastructure and in planning for timely expansions or upgrades.
- *Optimizing land use and infrastructure placement:* ML can assist in optimizing land use zoning and the placement of new infrastructure (e.g., transit lines,

power substations, and water treatment plants) to maximize accessibility, minimize environmental impact, and ensure equitable service distribution. For example, AI can optimize the infrastructure of the city by analyzing data from public transport, weather sensors, and pedestrian movement to ensure efficient utilization of resources [16].

5.2 Designing for resilience and sustainability

Traditionally, infrastructure design has often focused on meeting minimum performance standards under expected conditions. ML enables a shift toward designing systems that are inherently more resilient to unexpected events and more sustainable over their entire lifecycle through several considerations:

- *Performance simulation and evaluation:* ML models can be used to simulate the performance of different infrastructure designs in a wide range of scenarios, including extreme weather events (e.g., floods and heatwaves), seismic activity, demand surges, or component failures [7, 16, 25]. This allows designers to evaluate the resilience and sustainability implications of various design choices before construction.
- *Material optimization:* ML can optimize the selection and combination of construction materials to improve durability, reduce lifecycle costs, and minimize environmental impact. For example, ML algorithms have been shown to predict the ability of asphalt pavements with reclaimed asphalt materials to withstand moisture, promoting the use of recycled content [25]. In addition, AI-assisted bridge designs have been reported to potentially reduce concrete use by up to 30% while maintaining structural integrity [7].
- *Incorporating climate change projections:* ML can integrate climate change models and projections into the design process, helping to create infrastructure that is adapted to future climatic conditions, such as higher temperatures, increased flood risk, or water scarcity.

5.3 Generative design and novel infrastructure solutions

Beyond optimizing existing design paradigms, ML is also paving the way for generative design, where algorithms actively participate in creating novel infrastructure solutions:

- *Automated design generation:* Generative design methods, which may employ techniques such as graph variational autoencoders (GVAE) and graph convolutional networks (GCN) as discussed in the context of resilient interconnected critical infrastructure networks [4], can explore a vast design space and propose innovative solutions that meet predefined performance criteria for resilience, sustainability, and cost effectiveness.
- *Discovering unconventional designs:* ML can help discover unconventional but highly efficient and robust design configurations that human designers, constrained by traditional practices or cognitive biases, might not readily conceive of. This is particularly relevant for complex, multicomponent systems where interactions are non-intuitive.

- *Rapid prototyping and iteration:* ML-driven design tools can accelerate the design-evaluate-iterate cycle, allowing the rapid exploration of many design alternatives and leading to more optimal final solutions.

The integration of ML into infrastructure planning and design signifies an evolution from focusing primarily on initial construction costs and immediate functionality toward a more holistic and lifecycle-aware perspective. Traditional design processes often give less weight to long-term operational efficiency, maintenance burdens, resilience to future threats, and end-of-life considerations. However, the predictive capabilities of ML allow these critical lifecycle aspects to be explicitly modeled and incorporated into the initial design stages [7, 16, 25]. By simulating long-term degradation processes, forecasting maintenance needs under various operational and environmental conditions, and even assessing opportunities for material reuse or recycling at the end of an asset's service life, ML enables designers to optimize for total lifecycle cost, sustained performance, and minimal long-term environmental impact [7]. This shift means that infrastructure can be “born resilient” and “born sustainable,” rather than requiring costly retrofits or facing premature obsolescence. Decisions made with this foresight in the design phase have the most significant leverage in shaping the ultimate resilience and sustainability of infrastructure systems, moving the paradigm from simply “building strong” to “building smart for the long term.”

6. Challenges and considerations in implementing ML for infrastructure systems

Despite the immense potential of ML to revolutionize the development and management of sustainable and resilient interconnected infrastructure systems, its extensive adoption is accompanied by considerable challenges. These challenges encompass technical, ethical, and practical spheres, necessitating meticulous evaluation and strategic mitigation efforts.

6.1 Data-related challenges

Data are the foundation of ML, and issues related to its availability, quality, and characteristics are the primary challenges when it comes to data:

- *Availability and scarcity:* A significant challenge is the lack of sufficient historical operational data, particularly for low-probability, high-impact extreme events such as major natural disasters or sophisticated cyberattacks [4, 8]. Deep learning models, in particular, often require large amounts of data for effective training. This scarcity can hinder the development of robust ML models capable of generalizing to rare but critical scenarios.
- *Quality and heterogeneity:* ICISs generate data from a multitude of diverse sources, including various types of sensors, supervisory control and data acquisition (SCADA) systems, maintenance logs, weather services, and even social media. These data are often noisy, incomplete, inconsistent, and come in heterogeneous formats [8]. Ensuring data quality, cleaning, and effective fusion of disparate sources are complex and time-consuming prerequisites for a successful ML application.

- **Dimensionality:** The data collected from ICIS can be extremely high-dimensional, with numerous features that describe the states of the components, the operational parameters, and the environmental conditions. This “curse of dimensionality” can make ML models computationally expensive, prone to overfitting, and difficult to interpret [3, 8]. Effective feature selection and dimensionality reduction techniques are therefore critical for such cases [3].
- **Imbalanced datasets:** In many resilience applications, “failure” or “disruption” events are rare compared to normal operational states. This leads to imbalanced datasets where the class of interest (e.g., system failure) is vastly underrepresented, making it difficult for ML classifiers to learn effectively and potentially leading to poor prediction of these critical rare events [8]. **Figure 5** summarizes the challenges in ML data for CIs.

6.2 Data privacy and cybersecurity concerns

The increasing reliance on data and interconnectedness in ML-driven infrastructure systems introduces significant privacy and cybersecurity risks:

ML Data Challenges for Infrastructure Systems

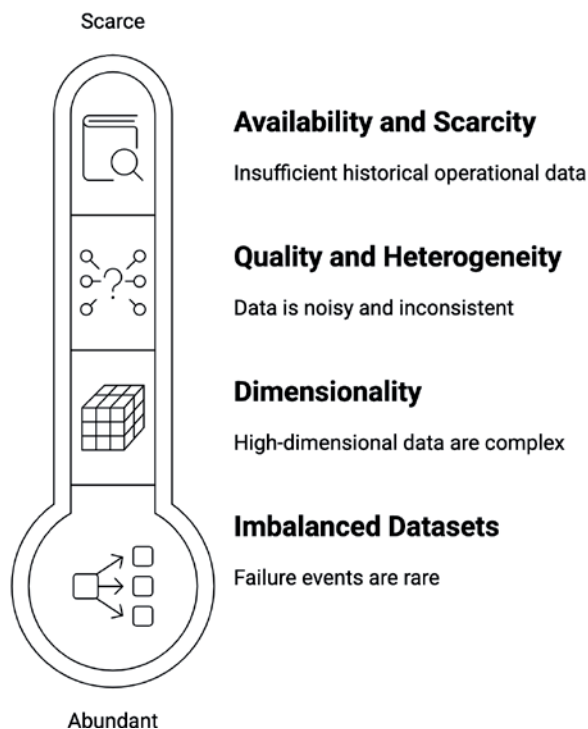


Figure 5.
A graphical summary of the challenges in ML data for CIs.

- *Sensitive data handling*: Infrastructure data, such as energy consumption patterns of individuals, water usage details, traffic movements, and critical operational parameters of power grids, can be highly sensitive. ML models often require access to granular data, raising concerns about user privacy and the potential for misuse if data is breached or inappropriately accessed [7, 8, 26–28]. Compliance with data protection regulations such as the General Data Protection Regulation (GDPR) is essential [26].
- *Vulnerability of ML systems to attacks*: ML models themselves can be targets of adversarial attacks, including:
 - *Data poisoning*: Malicious actors could inject corrupted data into the training set to compromise the performance of the model or introduce backdoors.
 - *Model evasion*: Attackers might craft inputs that are subtly altered to deceive a deployed ML model into making incorrect predictions (e.g., misclassifying a cyberattack as normal traffic).
 - *Model stealing/inference*: Attackers might attempt to reconstruct a proprietary ML model or infer sensitive training data by querying it.

The consequences of such attacks on critical infrastructure can be severe, ranging from operational disruptions to safety hazards [26, 27].

- *Securing data pipelines and IoT devices*: The entire data ecosystem, from IoT sensors collecting data to communication networks transmitting it and databases storing it, must be secured. Vulnerabilities in any part of this pipeline can compromise the data used by the ML models or the control signals generated by them. The proliferation of IoT devices significantly expands the attack surface [26].

6.3 Ethical implications of AI in infrastructure management

The deployment of AI and ML in critical infrastructure, which directly impacts public services and safety, raises profound ethical questions that need to be addressed proactively:

- *Algorithmic bias and fairness*: ML models are trained on historical data, which may reflect existing societal biases. If not carefully designed and audited, these models can perpetuate or even amplify these biases, leading to unfair or inequitable outcomes in resource distribution, service provision, or risk assessment [28, 29]. For example, a predictive policing model for infrastructure security, if trained on biased data, could disproportionately target certain communities.
- *Accountability and transparency (explainability)*: Determining who is responsible when an ML-driven decision leads to an adverse outcome (e.g., a power outage due to an incorrect predictive maintenance postponement or an accident caused by an AI-controlled traffic system) is a significant challenge. The “black box” nature of some complex ML models (e.g., deep neural networks) makes it difficult to understand their decision-making processes, hindering accountability and trust [8, 28, 29].

- *Job displacement and workforce transformation:* The automation capabilities of ML can lead to job displacement for human workers involved in the operation, maintenance, and monitoring of the infrastructure [28]. Although new roles requiring AI-related skills may emerge, there is a need for strategic workforce planning, reskilling, and upskilling programs to manage this transition.
- *Surveillance and erosion of privacy:* The increased sensorization and data collection necessary for many ML applications in smart cities and infrastructure can lead to increased surveillance of public and private activities, raising concerns about privacy erosion if not governed by strong ethical guidelines and regulations [28].

6.4 Model interpretability, trust, and robustness

For ML systems to be adopted in safety-critical infrastructure applications, they must be interpretable, trustworthy, and robust. Several characteristics need to be achieved for such ML-based applications:

- *Explainability or explainable AI (XAI):* There is a growing demand for ML models that can provide clear and understandable explanations for their predictions and decisions, rather than acting as opaque “black boxes” [8]. This is critical for debugging models, gaining regulatory approval, and building trust with human operators who need to act on ML-generated insights.
- *Building trust with operators and stakeholders:* Infrastructure operators and decision-makers may be reluctant to give up control or rely heavily on ML systems, especially if their internal workings are not well understood or if their reliability under all conditions has not been proven [8].
- *Robustness to novel conditions and adversarial perturbations:* ML models must be robust enough to generalize well to unseen scenarios and data distributions that may differ from their training data. They should also be resilient to small, potentially adversarial, perturbations in their input data that could cause them to make erroneous predictions.

6.5 Scalability and real-world deployment issues

Transitioning ML models from research prototypes to reliable operational systems in large-scale ICISs presents practical challenges including the following:

- *Computational demands:* Training complex ML models, especially deep learning architectures, on massive datasets can be computationally intensive, requiring significant hardware resources (e.g., graphics processing units (GPUs) and tensor processing units (TPUs)) and specialized expertise [8]. The deployment of these models for real-time inference in operational environments also has computational constraints.
- *Integration with legacy systems:* Much of the existing critical infrastructure is based on legacy control systems and data infrastructure. Integrating modern ML solutions with these older systems can be technically challenging and costly, requiring careful planning for interoperability and data exchange.

- *Need for skilled personnel:* The development, deployment, and maintenance of ML systems for infrastructure require a workforce with specialized skills in data science, ML engineering, and domain-specific infrastructure knowledge. There is currently a shortage of this talent [26].
- *Regulatory and standardization obstacles:* The regulatory landscape for AI in critical infrastructure is still evolving. Lack of clear standards for performance, safety, and security of ML systems can hinder their adoption.

The journey toward successfully integrating ML into ICISs is not merely a technological endeavor. In fact, it is profoundly a socio-technical challenge. The points discussed above, including data governance, cybersecurity, ethical frameworks, and the need for interpretability and trust, all highlight that human and organizational factors are as critical as algorithmic sophistication. Even the most advanced ML model will not deliver its potential benefits if it is not trusted by human operators [8], if its deployment violates societal ethical norms or privacy expectations [26, 29], or if it cannot be securely and robustly integrated into existing operational practices. Therefore, a holistic strategy is imperative, where it must encompass not only the development of cutting-edge ML algorithms, but also the establishment of robust data governance frameworks, comprehensive cybersecurity measures, clear ethical guidelines, extensive training and upskilling programs for the workforce, and proactive public engagement to build understanding and acceptance. An interdisciplinary approach, involving collaboration between engineers, computer scientists, data scientists, social scientists, policymakers, and the public, is essential to navigate these complexities and leverage the full and responsible potential of ML in shaping the future of interconnected infrastructure.

7. Conclusion: Future trends and transformative potential

ML is undeniably emerging as a pivotal technology in the evolution of interconnected infrastructure systems. Its capacity to analyze complex data, learn intricate patterns, and drive intelligent decision-making is fundamentally reshaping how these critical systems are planned, designed, operated, and maintained. The journey thus far has shown significant strides in leveraging ML for improved sustainability and increased resilience, but the revolutionary potential is far from fully realized.

7.1 Recap of the pivotal role of ML

Throughout this chapter, the diverse contributions of ML to ICISs have been explored. For *sustainability*, ML has proven to be essential in optimizing resource usage by enabling precise demand forecasting in the energy and water sectors, leading to reduced waste and more efficient operations [8, 15]. Furthermore, ML is a critical enabler for the large-scale integration of intermittent renewable energy sources by providing advanced forecasting and control mechanisms necessary for grid stability [12].

In the realm of *resilience*, ML improves the robustness of the system through predictive maintenance, allowing proactive interventions before failures occur, and through real-time anomaly detection that can alert to imminent problems or

malicious activities [9, 18]. In the post-disruption phase of resilience, ML can accelerate damage assessment using various data sources, including social media, and optimize complex restoration and resource allocation strategies through advanced techniques such as multiobjective optimization and reinforcement learning [4, 6, 24]. Domain-specific applications in transportation and water management further illustrate the practical benefits, from traffic flow optimization and leak detection to designing more durable materials [14, 25]. Even in the early stages of infrastructure planning and design, ML offers tools for more informed urban planning and the creation of inherently more sustainable and resilient structures [16].

7.2 Emerging ML paradigms and future research directions

The continued advancement of ML, coupled with a deeper understanding of infrastructure complexities, points toward several exciting future trends and research directions:

- *Physics-informed machine learning (PIML)*: This approach seeks to integrate domain knowledge, often in the form of physical laws and engineering principles (e.g., differential equations governing fluid dynamics or power flow), directly into ML models. By constraining ML models with known physics, PIML can lead to more accurate and generalizable models that require less training data and provide more physically plausible predictions, which is essential for safety-critical infrastructure applications [8].
- *Digital twins*: ML-powered digital twins—virtual and dynamic replicas of physical ICISs—are becoming increasingly complex. These allow real-time monitoring and simulation of “what if” scenarios (e.g., impact of extreme weather or efficacy of different response strategies) and optimization of operational and resilience strategies in a risk-free environment before deployment in the actual system [8].
- *Federated learning and privacy-preserving ML*: To address data privacy concerns, federated learning allows ML models to be trained collaboratively across multiple decentralized data sources (e.g., different utility companies or smart city sensors) without exchanging raw sensitive data. Only model updates or aggregated parameters are shared, improving privacy while still enabling collective learning.
- *Advanced reinforcement learning*: The application of RL in ICIS management is expected to grow, with more advanced agents capable of handling complex, partially observable, and multi-agent environments. This includes areas such as autonomous grid control, adaptive traffic management, and dynamic resource allocation during cascading failures [4, 11, 24].
- *Graph neural networks*: Given that infrastructure systems are inherently networks with complex topologies and interdependencies, GNNs are particularly well suited for modeling these relationships. Future research will likely explore a wider application of GNNs for tasks such as link prediction (identifying hidden interdependencies), node classification (criticality assessment), and graph-level predictions (overall system vulnerability or resilience) [4, 17].

- *Hybrid AI models*: Combining the strengths of different ML techniques (e.g., deep learning for feature extraction, symbolic AI for reasoning, and optimization algorithms for decision-making) and integrating them with traditional engineering models will lead to more robust and versatile solutions [3, 6].
- *Improved uncertainty quantification (UQ)*: For critical decisions in infrastructure management, understanding the uncertainty associated with ML predictions is vital. Future research is expected to focus on developing more robust UQ methods for complex ML models, providing confidence intervals and probabilistic outputs that better inform risk assessment and decision-making [30].
- *Human-in-the-loop ML and XAI*: Integrating human expertise more effectively into ML workflows and developing XAI techniques that provide transparent and interpretable insights are critical to building trust and ensuring that ML systems align with human operational goals and ethical considerations [4, 8]. A summary of these future trends is illustrated in **Figure 6**.

7.3 The path toward smarter, resilient, and adaptive infrastructure

The long-term vision of ML-driven infrastructures is one in which ICISs are not only managed more efficiently but possess inherent intelligence. Future infrastructures may be capable of autonomously anticipating disruptions through sophisticated predictive analytics, adaptively reconfiguring operations in real time to mitigate impacts, and even initiating self-healing processes to restore functionality with minimal human intervention. This involves moving beyond isolated ML applications to creating integrated and system-wide intelligence where different ML agents and

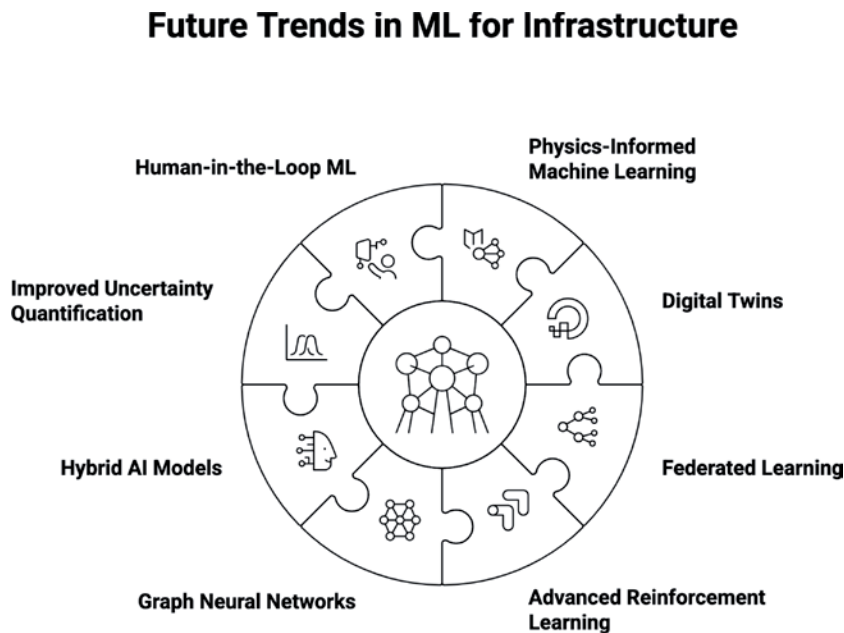


Figure 6.
Graphical summary of ML future trends in ICISs.

models coordinate to optimize for global sustainability and resilience objectives. Such an intelligent infrastructure system would continuously learn from new data, adapt to evolving conditions (e.g., climate change, demographic shifts, or new technologies), and improve its performance over time.

7.4 Call for interdisciplinary collaboration and continued research

Realizing the full potential of ML in ICISs requires extensive and sustained research efforts, along with robust interdisciplinary collaboration. The challenges outlined, including data, security, ethics, interpretability, and deployment, cannot be solved by ML experts or domain engineers working in isolation. A collaborative effort involving computer scientists, civil and environmental engineers, urban planners, policymakers, social scientists, and the public is required. This collaboration is essential for developing technically sound, ethically responsible, and socially acceptable ML solutions. Continued investment in research is essential to advance fundamental ML capabilities, develop domain-specific applications, create robust testing and validation frameworks, and establish appropriate governance and regulatory structures.

At its core, the integration of ML into interconnected infrastructure systems is more than an incremental improvement; indeed, it represents a potential paradigm shift. The trajectory points toward transforming infrastructure from relatively static, engineered constructs that are passively managed into dynamic, learning, and adaptive socio-technical ecosystems. As ML becomes more deeply embedded, the infrastructure will gain unprecedented capabilities for self-awareness (understanding its own state and environment), self-regulation (optimizing its performance autonomously), and even self-improvement (learning from experience to improve future resilience and sustainability). This evolution could redefine what we mean by “infrastructure,” moving from a model of “building and maintaining” to one of “cultivating and evolving” these vital systems. This transformation has profound implications for how we approach urban planning, resource management, and societal resilience in an increasingly complex and uncertain world, offering a path to a more sustainable and secure future.

Acronyms

AI	artificial intelligence
ANN	artificial neural network
ARIMA	autoregressive integrated moving average
BBN	Bayesian belief network
CI	critical infrastructure
CNN	convolutional neural network
DeepONets	deep operator networks
DQN	deep Q-learning
DRL	deep reinforcement learning
ESS	energy storage systems
FFNN	feedforward neural network
GCN	graph convolutional network
GNN	graph neural network
GPR	Gaussian process regression
GVAE	graph variational autoencoder

HMM	hidden Markov model
ICISs	interconnected infrastructure systems
ICT	information and communication technology
IEEE	institute of electrical and electronics engineers
IoP	internet of people
IoT	internet of things
LTD	learn-to-decompose
LSTM	long short-term memory
MADRL	multi-agent deep reinforcement learning
ML	machine learning
MOEA/D	multiobjective evolutionary algorithm based on decomposition
NLL	negative log-likelihood
NLP	natural language processing
NRW	non-revenue water
OLS	ordinary least squares
OPF	optimal power flow
PCA	principal component analysis
PIML	physics-informed machine learning
RES	renewable energy sources
RL	reinforcement learning
RSS	residual sum of squares
RUL	remaining useful life
SCADA	supervisory control and data acquisition
SDGs	sustainable development goals
SSE	sum of squared errors
SVM	support vector machine
UQ	uncertainty quantification
VQ	vector quantization
WDS	water distribution systems
WWTP	wastewater treatment plant
XAI	explainable AI

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References

- [1] Haggag M, Ezzeldin M, El-Dakhakhni W, Hassini E. Resilient cities critical infrastructure interdependence: A meta-research. *Sustainable and Resilient Infrastructure*. 2020;7(4):291-312
- [2] Osei-Kyei R, Almeida LM, Ampratwum G, Tam V. Systematic review of critical infrastructure resilience indicators. *Construction Innovation*. 2022;23(5):1210-1231
- [3] Balakrishnan S, Cassottana B, Verma A. Application of clustering algorithms for dimensionality reduction in infrastructure resilience prediction models. *arXiv*. 2022;1:1-13
- [4] Alkhaleel BA. Machine learning applications in the resilience of interdependent critical infrastructure systems—A systematic literature review. *International Journal of Critical Infrastructure Protection*. 2024;44:100646
- [5] Rinaldi SM, Peerenboom JP, Kelly TK. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems*. 2001;21(6):11-25
- [6] Aslani B, Mohebbi S. Learn to decompose multiobjective optimization models for large-scale networks. *International Transactions in Operational Research*. 2022;31:949-978
- [7] Abbas A, Duijster D. Smart Urban Infrastructure: AI-Powered Solutions for Sustainable Transportation and Construction Project Optimization. 2025. Available from: https://www.researchgate.net/publication/388489903_Smart_Urban_Infrastructure_AI-Powered_Solutions_for_Sustainable_Transportation_and_Construction_Project_Optimization.
- [8] Wang J, Pinson P, Chatzivasileiadis S, Panteli M, Strbac G, Terzija V. On machine learning-based techniques for future sustainable and resilient energy systems. *IEEE Transactions on Sustainable Energy*. 2023;14(2):1230-1243
- [9] Ramineni G, Ghorbani-Renani N, Barker K, González AD, Razzaghi T, Radhakrishnan S. Machine learning approaches to modeling interdependent network restoration time. *Environment Systems and Decisions*. 2022;43:22-35
- [10] Murphy KP. Machine learning - a probabilistic perspective. In: *Adaptive Computation and Machine Learning Series*. Cambridge, Massachusetts: MIT Press; 2012
- [11] Murali PS, Mohebbi S. Hybrid simulation and reinforcement learning-based scheduling for resilient infrastructure networks. In: *2024 Winter Simulation Conference (WSC)*. Piscataway, New Jersey: IEEE; 2024. pp. 786-797
- [12] Allal Z, Noura HN, Salman O, Chahine K. Machine learning solutions for renewable energy systems: Applications, challenges, limitations, and future directions. *Journal of Environmental Management*. 2024;354:120392
- [13] Daniel C, Gehin J, Laurin-Kovitz K, Morreale B, Stevens R, Tumas W. *Advanced Research Directions on AI for Energy*. Alexandria, VA: US Department of Energy; 2024
- [14] Grbčić L, Kranjčević L, Družeta S. Machine learning and

- simulation-optimization coupling for water distribution network contamination source detection. *Sensors*. 2021;**21**(4):1157
- [15] Taloma RJL, Cuomo F, Communiello D, Pisani P. Machine learning for smart water distribution systems: Exploring applications, challenges and future perspectives. *Artificial Intelligence Review*. 2025;**58**(4):120
- [16] Hameed A, Ahmed SS, Rasel ABS, Hamim M, Sok M, Tesfalem A. The role of artificial intelligence in revolutionizing construction Project Management: Enhancing efficiency and sustainability. *North American Academic Research (NAAR)*. 2025;**8**:56-76
- [17] Wang S, Gu X, Luan S, Zhao M. Resilience analysis of interdependent critical infrastructure systems considering deep learning and network theory. *International Journal of Critical Infrastructure Protection*. 2021;**35**:100459
- [18] Ntalampiras S, Soupionis Y, Giannopoulos G. A fault diagnosis system for interdependent critical infrastructures based on HMMs. *Reliability Engineering and System Safety*. 2015;**138**:73-81
- [19] Kasmi O, Baina A, Bellaflkih M. Fuzzy logic based clustering algorithm for management in critical infrastructure. *Cluster Computing*. 2020;**24**(1):433-458
- [20] George JO, Elayan S, Sykora M, Solter M, Feick R, Hewitt C, et al. The role of social media in building pandemic resilience in an urban community: A qualitative case study. *International Journal of Environmental Research and Public Health*. 2023;**20**(17):6707
- [21] Rachunok B, Bennett J, Flage R, Nateghi R. A path forward for leveraging social media to improve the study of community resilience. *International Journal of Disaster Risk Reduction*. 2021;**59**:102236
- [22] Yuan F, Liu R, Mao L, Li M. Internet of people enabled framework for evaluating performance loss and resilience of urban critical infrastructures. *Safety Science*. 2021;**134**:105079
- [23] Dhulipala SLN, Hruska RC. Efficient interdependent systems recovery modeling with DeepONets. *arXiv*. 2022:1-6
- [24] Liang H, Moya B, Chinesta F, Chatzi E. Resilience-based post disaster recovery optimization for infrastructure system via deep reinforcement learning. *arXiv*. 2024;**265**(A):111478
- [25] Golafshani E, Khodadadi N, Ngo T, Nanni A, Behnood A. Modelling the compressive strength of geopolymers recycled aggregate concrete using ensemble machine learning. *Advances in Engineering Software*. 2024;**191**:103611
- [26] Khan M. Cybersecurity in Critical Infrastructure: Challenges and Future Directions. 2025. Available from: https://www.researchgate.net/publication/388806231_Cybersecurity_in_Critical_Infrastructure_Challenges_and_Future_Directions.
- [27] Maglaras L, Janicke H, Ferrag MA. Cybersecurity of critical infrastructures: Challenges and solutions. *Sensors*. 2022;**22**(14):5105
- [28] Wong LPW. Artificial intelligence and job automation: challenges for secondary students' career development and life planning. *Merits*.

2024;**4**(4):370-399. DOI: 10.3390/merits4040027

[29] Nobles C. 21. In: *Offensive Artificial Intelligence in Cybersecurity: Techniques, Challenges, and Ethical Considerations*. Hershey, Pennsylvania: IGI Global; 2023. pp. 348-363

[30] Alkhaleel BA, Liao H, Sullivan KM. Model and solution method for mean-risk cost-based post-disruption restoration of interdependent critical infrastructure networks. *Computers and Operations Research*. 2022;**144**:105812

Chapter 4

Transportation Infrastructure Health Monitoring

Ebenezer Fanijo, Jian Liu and Taofiq Mohammed

Abstract

Civil infrastructure, commonly referred to as the built environment, comprises essential systems such as buildings, roads, bridges, and dams that support societal governance, commerce, and economic development. However, these structures begin to deteriorate shortly after construction. In the United States, over 42% of bridge structures constructed post-1940 have been classified as structurally deficient, underscoring the urgent need for robust monitoring and maintenance systems. According to the recent ASCE Report Card, much of the U.S. infrastructure has exceeded its intended service life, requiring immediate attention in terms of rehabilitation, sustainability, and preservation to ensure public safety and functionality. Traditional methods such as visual inspections and non-destructive evaluation have served as the primary means of infrastructure assessment but often fail to detect critical subsurface or localized damage. This chapter provides a comprehensive review of the current state of civil infrastructure in the U.S. and selected developing regions, highlighting advancements in structural health monitoring systems. Emphasis is placed on the application and implementation of sensor-based instrumentation, including fiber optics, for real-time data collection, damage detection, and predictive analytics through data mining techniques. The chapter also explores future directions for enhancing infrastructure diagnostics and long-term performance monitoring.

Keywords: civil infrastructure, structural health monitoring, non-destructive evaluation, sensor instrumentation, fiber optics

1. Introduction

Civil infrastructures sometimes referred to as the ‘built-environment’ have been a fundamental part of modern societies for governance, commerce, economic and social growth [1, 2]. According to Sanghyeok et al., many of the civil structures constructed years ago are deteriorating and are under-performing [3]. Civil infrastructure such as buildings, highways, dams, tunnels bridges was constructed 50 or more years ago. The rate of infrastructure aging begins from the time of construction and the advert effect is felt many years after [1]. Over the previous decades, numerous reports have been documented on civil infrastructure deterioration in Korea, China, Europe, Asia, and North America. For instance, Asia countries have also experienced a decrease rate of infrastructure performance where 10% of her infrastructure is

aging rapidly each year [3]. In the United States, 42% of the bridge structures built after the 1940s has been reported to be structurally deficient [3].

The quality and safety of human life are closely tied to the performance of civil infrastructure systems. As these systems age, their deterioration not only undermines national development efforts but also poses increasing social and economic risks [4, 5]. Cutter et al., 2003 highlight that infrastructure failures, particularly in transportation, bridges, water, and sewer systems, can escalate into disasters, leading to substantial loss of property and life [6]. Roadway conditions are a particularly pressing concern. Poorly maintained roads and highways contribute significantly to traffic accidents, surpassing many other causes of roadway fatalities [7–10]. According to the American Society of Civil Engineers (ASCE), the overall state of U.S. infrastructure received a cumulative GPA of C in 2025, a modest improvement from the C- issued in 2021 [11, 12]. However, specific categories remain troubling: roads received a D and bridges a C. Nearly 45% of the nation's 623,218 bridges are over 50 years old, with 7% classified as structurally deficient. Additionally, 20% of highway miles are reported to be in poor condition. The cost to rehabilitate and upgrade critical infrastructure is staggering: an estimated \$151 billion for highways, \$115 billion for bridges, and \$165 billion for dams - each reflecting urgent needs as infrastructure elements rated D continue to degrade [11]. **Table 1** provides a summary of ASCE ratings since 1988, revealing that the majority of U.S. civil infrastructure remains in poor to fair condition. This signals ongoing deterioration and a looming risk to both public safety and national resilience in the coming years.

The current state of civil infrastructure in the United States reflects a critical need for immediate investment and proactive management. Without intervention, the deteriorating condition of roads, bridges, water systems, and other key assets is projected to cost the U.S. economy over \$3.9 trillion in lost GDP, \$7 trillion in lost business sales, and 2.5 million job losses by 2025. This challenge is not unique to the United States. Other developed nations, including the United Kingdom, Australia, and Canada, also face similar issues with aging and underperforming infrastructure [11, 14–19]. Global assessments consistently indicate that the overall condition of national infrastructure systems is below average and lacks long-term resilience strategies. Notably, as shown in **Figure 1**, only China and Singapore have received infrastructure scores above 0.65 on a normalized 1.0 scale [20].

Year	Bridges	Roads	Dams	Overall
1988	—	C+	—	C
1998	C-	D-	D	D
2001	C	D+	D	D+
2005	C	D	D+	D
2009	C	D-	D	D
2013	C+	D	D	D+
2017	C	D	D	D+
2021	C	D	D	C-
2025	C	D	D	C

Table 1.
ASCE ratings for bridges, roads and dams from 1988 [11–13].

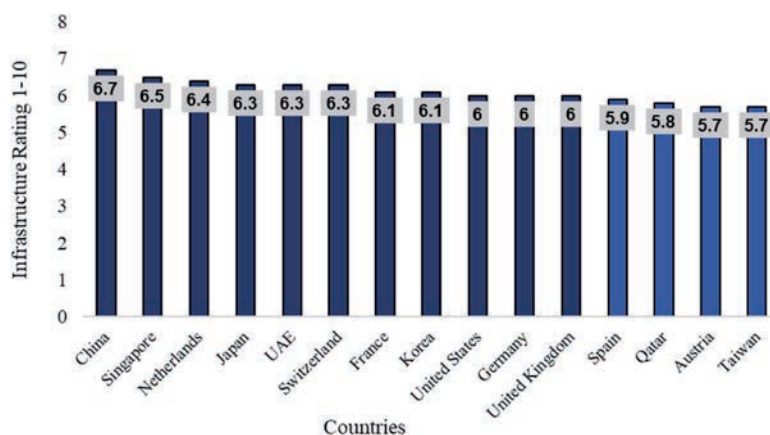


Figure 1.
 Infrastructure rating on scale 1–10 for each country [20].

These conditions highlight the pressing need for infrastructure rehabilitation, sustainable design, and life-extension practices, where many systems have already exceeded their intended service life. Safe and reliable civil infrastructure is essential not only for public well-being but also for economic security and resilience. One of the most promising strategies for reversing this decline is civil infrastructure monitoring. This proactive approach involves the integration of sensing, diagnostics, and analytics during and after construction, allowing for early detection of defects, streamlined maintenance, and lifecycle cost assessments. Such monitoring not only improves safety and performance but also reduces long-term costs and extends infrastructure service life. As a result, infrastructure health monitoring has become a central focus in civil engineering research and practice, underpinning efforts to modernize national infrastructure systems. Thus, this chapter provides a comprehensive review of the current state of civil infrastructure in the U.S. and selected developing regions, highlighting advancements in structural health monitoring systems. Emphasis is placed on the application and implementation of sensor-based instrumentation, including fiber optics, for real-time data collection, damage detection, and predictive analytics through data mining techniques. The chapter also explores future directions for enhancing infrastructure diagnostics and long-term performance monitoring.

2. The rising importance of civil Infrastructure monitoring

In recent years, civil infrastructure monitoring has gained significant attention in both the civil engineering community and at the national policy level. Many U.S. civil structures have exceeded their intended service life, prompting urgent needs to improve their sustainability, resilience, and maintenance strategies [21, 22]. Additionally, increasing exposure to extreme events, such as earthquakes, hurricanes, and tornadoes, has underscored the vulnerability of aging infrastructure and the need for tools to evaluate structural performance and recovery capacity [23, 24]. Two main approaches to structural monitoring are widely recognized: local and global monitoring. Local monitoring is designed to detect small-scale defects, such as micro-cracks, and often employs visual inspections or non-destructive evaluation

(NDE) techniques. Global methods, by contrast, detect larger, system-level damage but may miss early-stage defects that compromise long-term integrity [23, 25]. A stark example is the *I-35 W bridge collapse* in Minneapolis. Although inspected regularly, structural weaknesses in hard-to-access gusset plates went undetected. Corrosion and damage levels were underestimated due to the limits of visual inspection, ultimately contributing to the catastrophic failure [23, 26, 27]. This event highlighted the need to move beyond visual assessments.

Despite its foundational role, traditional NDE, using techniques like X-ray imaging, ultrasonics, guided wave testing, and acoustic emission, has notable limitations. These include high labor demands, limited access to hidden components, safety risks, and difficulty detecting subsurface flaws [28–30]. In response, Structural Health Monitoring (SHM) systems have emerged as a transformative solution. SHM uses distributed networks of advanced sensors, often based on fiber optics, to continuously evaluate a structure’s real-time condition and remaining service life. These systems enable proactive maintenance, reduce risk, and enhance infrastructure safety and longevity. The evolution and implementation of SHM technologies will be explored in the following section.

3. Motivation for structural health monitoring

SHM has become essential for aging infrastructure and for assessing damage from external events like earthquakes and hurricanes. SHM systems provide ongoing updates on structural condition, continuous monitoring and damage diagnostics, and performance under extreme loading, enabling extended service life and reduced life-cycle costs [31–39]. SHM provides a systematic framework that collects, transmits, and interprets data through a network of sensors. These systems assess real-time deterioration, estimate remaining service life, and inform maintenance decisions. SHM thus supports condition-based monitoring, replacing less effective time-based maintenance schedules [40–42]. SHM can be seen as an advanced tool that both detects a “patient” sickness, finds the precise location of illness, and the cause as well as the effect of the symptoms [43]. In this scenario, SHM is the acquisition of data, transmitting and interrogating this set of data, and then decide (decision making)

People	Information	Science & Tech	Deployment
Designers and Engineers	Design details	Sensors	Networks
Materials specialist	Expected response and service life	Network connectivity	Collaboration
Damage analysis	Field response	Data acquisition and archival	Updating and Validation
IT specialist	Local & environmental conditions	Damage algorithms	Data selection and storage
Sensors specialist	Threshold	Capacity and service-life determinator	Assessment
Modelers	Sensor details	Reliability and serviceability prognosis	New design methodologies

Table 2.
Elements of SHM system.

from them. The critical element of this system can be categorized into people, information, science and technology, and deployment. A detailed version of these SHM elements is presented in **Table 2**. In summary, a typical SHM system has a sensor system, a data processing system (which includes acquiring, transmission, interrogating, and storing data) and a health evaluation system (diagnostic algorithms and information management). This element made it suitable to be regarded as an optimal design in the future. Local and global health techniques are only used for monitoring structure damage.

4. SHM application and data analysis

In this chapter an overview of structural health monitoring in terms of its application to civil infrastructure together with data analysis which make-up for complete monitoring design. This entails the fundamental knowledge, technology needs, and the challenges of SHM applications. A highlight was also given to data analysis and interpretation which is an essential aspect of implementing SHM. These are debated in terms of system or structure characterization, sensing technology, data quality, presentation, and making quality decisions.

4.1 SHM application and data analysis

Establishing clear monitoring objectives is essential to effective SHM system design. While universally accepted definitions of “health” and “performance” remain elusive, significant guidance is available from the ASCE SEI Technical Committee on performance-based design [44, 45]. In bridge assessments, condition indices such as displacement and frequency shifts are widely used. For pavements, the Present Serviceability Index (PSI) is common, rating conditions from 5 (excellent) to 0 (poor) [46–48]. Performance is evaluated based on limit-state criteria, where exceedance of predefined thresholds indicates functional failure. The reliability index is often used as a performance metric and can be derived from SHM data and simulation models [49, 50]. Thus, SHM not only quantifies structural condition (health) but also assesses structural integrity under service loads and extreme events (performance) [43, 51]. SHM has broad applications beyond the U.S.—notably in the U.K., China, and Korea—particularly for bridges, highways, and other transportation infrastructure. Its implementation extends to buildings, dams, water systems, and aerospace structures. Key monitoring parameters include deformation geometry, intrinsic and extrinsic forces, material degradation, and stress distribution across critical regions.

4.2 SHM application to new infrastructures

The application of SHM in new civil infrastructure serves as a proactive tool for capturing critical data during the fabrication and construction phases [52]. It enables the measurement of intrinsic forces, deformations, and stress distributions that may arise due to complex structural geometries or hazardous construction environments. Integrating SHM into the design phase allows anticipated construction-induced effects—such as stress, displacement, or distortion—to be accounted for from the outset [53]. This approach enhances construction safety, especially under high-risk conditions like hurricanes, seismic activity, or typhoons, which may occur during the

construction lifecycle. For instance, several bridges in East Asia have incorporated SHM systems specifically to monitor seismic and typhoon-related stresses. Moreover, SHM during early stages helps identify errors or inconsistencies in fabrication and construction drawings, preventing delays and costly rework. By continuously monitoring structural response, SHM offers immediate feedback that supports informed decision-making and quality assurance. A notable example is the Incheon Bridge in South Korea, where SHM was embedded from the design stage to monitor performance throughout construction and service life.

4.3 SHM application to new infrastructures

Just as SHM enhances new construction, it plays a critical role in managing aging or deteriorating infrastructure. For structures that have surpassed their design life, SHM enables the identification of underlying causes of distress—such as excessive deflection, cracking, vibration, corrosion, or alkali-silica reaction (ASR), supporting informed decisions for maintenance or preservation. By providing continuous, real-time data on mechanical (e.g., deflection, geometry changes, stress) and durability-related issues (e.g., corrosion, sulfate attack), SHM allows engineers to: Diagnose the root cause of performance degradation, Design targeted repair or retrofit strategies that maintain structural integrity and Extend service life without unnecessary replacement [53].

In cases where a structure has reached the end of its fatigue life or exhibits poor system reliability, SHM data may prompt a retrofit. This enhances reliability and safety without compromising the original structure. Moreover, SHM is valuable when applied statistically across a population of similar infrastructure [54]. For example, reinforced concrete decks supported by steel girders can be grouped based on shared attributes—load rating, failure mode, or system reliability. Monitoring a representative sample enables extrapolation of results to the broader group, optimizing decision-making on a scale and minimizing monitoring costs.

4.4 Planning and implementation of SHM systems

A successful SHM application begins with clearly defined objectives, essential requirements, and realistic expectations. Establishing these foundations enables engineers to address specific structural questions such as load capacity, stress distribution, displacement behavior, and uncertainties related to construction processes, structural condition, or remaining service life. When well-articulated, such goals can help reveal early damage, support hazard and accident evaluations, inform efficient maintenance strategies, and provide an objective assessment of present and future conditions while also addressing structural security concerns [52].

Once objectives are set, several critical components guide the implementation of SHM. Structural system characterization is the first step, involving a clear understanding of the infrastructure and its behavior. This includes determining the spatial scope of monitoring—whether localized, region-specific, or distributed across the entire structure—as well as specifying the type of instrumentation and duration of monitoring [52]. For example, a major bridge may require detailed, long-term monitoring using multiple sensor nodes and controlled loading scenarios due to its complexity and scale.

Measurement identification is another essential task. It requires determining which parameters best align with project goals. These may include load-induced

responses, serviceability indicators, construction impacts, environmental effects, or operational conditions. Typical measurements involve force, strain, displacement, rotation, temperature, vibration, and traffic volume. It is also important to evaluate the interactions between measured variables and ensure they are captured at the most informative physical locations.

Selecting appropriate sensing and data acquisition systems follows next. This includes specifying sensor types, installation procedures, calibration requirements, data transmission environments, and signal quality controls. A robust sensor plan ensures reliable data collection under both short-term and long-term monitoring conditions. Proper configuration, calibration, and validation protocols must also be implemented to ensure the system performs as intended throughout the project duration.

Data quality assurance and processing depend heavily on the robustness of the sensing infrastructure and the volume of collected data. Effective strategies must be in place at each step of the signal pathway—from sensor calibration to installation verification and signal validation—to minimize error propagation and reduce measurement uncertainty. These multi-level checks ensure data integrity and improve the reliability of conclusions drawn from the SHM system.

Finally, the collected data must be effectively presented and used to support decision-making. The SHM system should be able to interpret incoming signals, identify when thresholds are exceeded, compare results against predefined criteria, and, ideally, support automated or semi-automated decision execution. This data-to-decision process ensures the monitoring system functions not just as a passive observer but as an active tool for infrastructure management.

4.5 SHM data analysis

Numerous algorithms have been developed for analyzing and interpreting SHM data [25]. Effective SHM implementation requires integrating one or more of these methods across four key data analysis levels. These levels are structured to progressively extract meaningful insights from raw sensor outputs to actionable future performance predictions. Level 1 involves raw data indicators—direct readings from sensors without processing. Level 2, the identification stage, employs analytical methods to detect significant changes, such as damage or deterioration, over time. Level 3 incorporates detailed data analysis to localize and quantify these changes, yielding high-confidence assessments. Level 4 extends to prediction, using historical patterns to forecast future structural performance. Common techniques in SHM data analysis include statistical pattern recognition, parameter estimation via model updating, reliability and risk analysis, Bayesian inference, and computational modeling [25, 55, 56].

4.5.1 Statistical pattern recognition

This technique is adept at managing large datasets and identifying temporal changes. It typically includes three stages: data collection, feature extraction, and classification [57–60]. Features, quantitative descriptors, are then analyzed using supervised or unsupervised learning algorithms (**Figure 2**). Supervised learning is applied when labeled data from damaged and undamaged states are available, using classification or regression models. In contrast, unsupervised learning handles data from unknown states, using outlier detection or clustering. Sohn et al. summarized

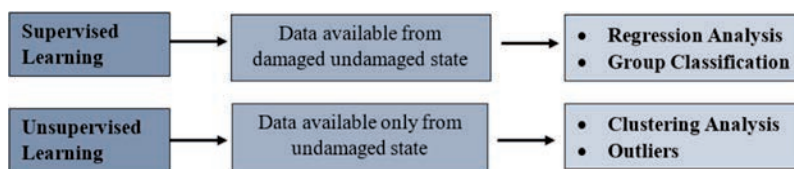


Figure 2.
Supervised and Unsupervised learning Approach for SHM.

the process into operational evaluation, data acquisition, feature extraction, and statistical modeling [61]. Metrics like natural frequency, AR model coefficients, and MAC are commonly used.

4.5.2 Parameter estimation with sensor fusion and model updating

At Level 3 analysis, sensor fusion and analytical model updating improve data reliability. This method of data analysis has been adopted by many researchers [62–65]. This approach estimates structural properties such as stiffness and Young’s modules using optimization techniques or empirical data. The result serves as a reference model for further assessment. Studies by Francoforte (2007) and Sanayei et al. (2006), demonstrated the value of this method in producing consistent and reliable structural insights [64, 66].

4.5.3 Reliability and risk analysis

Reliability analysis, although less explored in SHM, it plays a vital role in predicting failure probabilities and informing lifecycle management [59, 67]. It uses SHM data to assess whether structures remain within defined safety margins. Limit-state functions, constructed using stress and capacity parameters, distinguish between healthy and failed states. The reliability index (beta) quantifies the probability of failure and is calculated from the mean and standard deviation of structural parameters. Sensor-based models allow real-time monitoring and trigger alerts when reliability thresholds are breached.

4.5.4 Prediction and Bayesian analysis

Bayesian inference offers a powerful probabilistic framework to model uncertainty and predict future performance. It updates predictions as new SHM data becomes available, supporting real-time prognosis. Bayesian networks are especially useful in assessing current conditions and projecting future degradation in structures like bridges, using prior and sampling distributions to generate posterior outcomes.

In bridges, the technique is employed to determine the critical current state (structural performance and the structural health) from newly available data. In making quality decisions, good prediction (prognostic evaluation) is necessary, with the Bayesian model and sensor-based data this prognostic evaluation can be estimated. This is an invaluable tool for the management of structures such as bridges, dams, buildings, etc. [38]. A typical Bayesian model is expressed below.

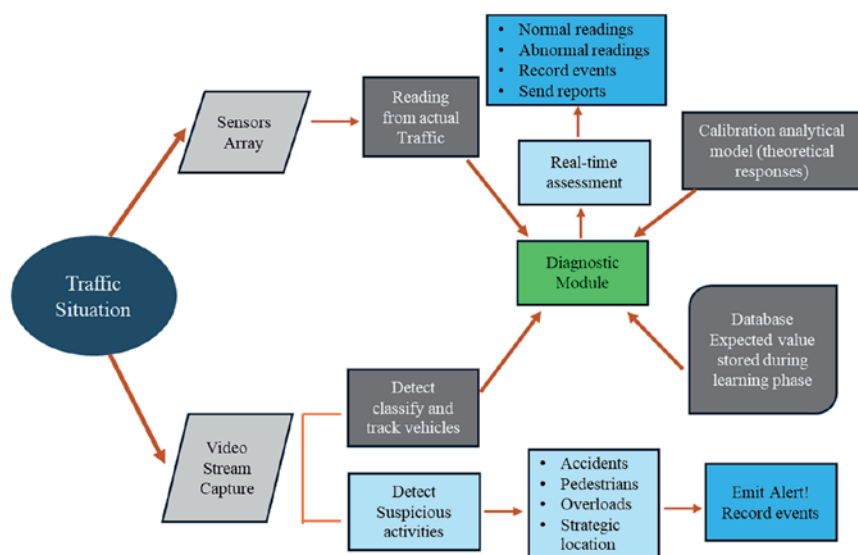


Figure 3.
 Integration of computational vision into SHM data [68].

$$g(\theta | \mathbf{x}) = \frac{f(\mathbf{x} | \theta)g(\theta)}{\int f(\mathbf{x} | \theta)fg(\theta)d\theta} \quad (1)$$

where $g(\theta | \mathbf{x})$ = posterior distribution (prognosis).

$f(\mathbf{x} | \theta)$ is the sampling distribution.

$g(\theta)$ is the prior distribution, θ is the continuous parameter vector and $\mathbf{x}$ is sample data.

4.5.5 Computational analysis, modeling, and simulation

Computer vision and simulation have revolutionized SHM by enabling image-based analysis of structural behavior. Streamed video and sensor data are integrated to assess real-time parameters such as traffic loads and stress distribution. By correlating visual data with simulation models, engineers can detect and track deterioration, facilitating timely interventions. Applications by [68] have demonstrated how such systems can automate maintenance scheduling and failure prevention through continuous visual monitoring. A typical integration of computer vision into SHM is shown in **Figure 3**.

5. Sensors and wireless sensing networks

SHM systems were introduced to replace traditional visual inspections, offering real-time, continuous assessment of structural integrity, damage, and remaining service life through sensor networks. Conventional SHM setups, relying on wired sensors such as accelerometers and vibrators, often suffer from high costs and logistical

challenges, particularly in large infrastructure systems. For instance, monitoring a multi-story building can cost \$5000 per sensing channel [69], while installing 84 wired accelerometers on the Bill Emerson Memorial Bridge costs approximately \$15,000 per channel [70]. Similarly, installing 350 sensors on the Tsing Ma Bridge in Hong Kong reached \$8 million [67]. Maintenance costs also escalate over time, further limiting scalability.

5.1 Wireless sensor networks (WSN)

To address these limitations, WSNs have emerged as a cost-effective and scalable solution. Enabled by advances in micro-electro-mechanical system MEMS, integrated circuits, and wireless communication, WSNs simplify installation, facilitate flexible sensor placement, and streamline data acquisition [71]. A WSN system typically comprises software for data collection and processing, and hardware including sensors and central servers (**Figure 4**) [72]. While performance depends on sensor placement, environmental conditions, and communication bandwidth, WSNs significantly reduce SHM implementation costs [73].

Smart wireless sensors further enhance SHM capabilities. These sensors integrate onboard microprocessors, wireless communication, sensing modules, and low-power batteries to enable self-diagnostics and in-situ processing [74]. Their decision-making capacity improves data quality and enables localized damage detection. Over the past two decades, smart sensors have been widely deployed in civil infrastructure applications [75–80].

The iMote2, developed at the University of California-Berkeley and commercialized by Crossbow, is among the most advanced SHM sensor platforms. It offers superior storage, reduced synchronization errors, and middleware support for large-scale deployments [81]. WSN platforms such as MICA2, WiMMS, RIMS, Husky, and DuraNode have also been implemented successfully [82]. A notable full-scale deployment occurred on the second Jindo Bridge in South Korea, where 71 iMote2-based WSN nodes provided 427 sensing channels to monitor bridge components [36, 83]. Similarly, the Meriden Bridge project demonstrated the integration of 5 iMote2 WSNs with 38 wired sensors for comprehensive health monitoring [84].

5.2 Application of wireless sensor

Wireless sensors are not conventional standalone devices but rather integrated data acquisition nodes comprising various structural sensing elements, onboard microprocessors, and wireless communication modules. These nodes typically incorporate accelerometers, strain gauges, seismometers, velocity gauges, displacement

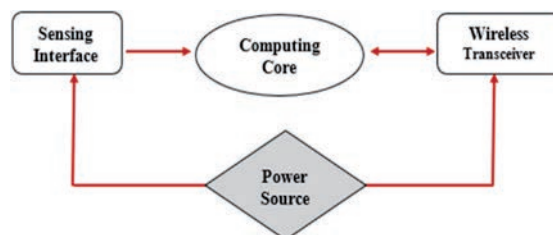


Figure 4.
The subsystem of wireless sensors (adopted from Ref. [72]).

transducers, and inclinometers to assess the physical state of structures [72]. Their application within smart wireless sensor networks varies depending on structural type and required performance metrics.

A prime example is the Akashi Kaikyo Bridge in Japan, the world's longest suspension bridge, which employs a comprehensive sensor suite—including accelerometers, seismometers, velocity and displacement gauges, thermometers, GPS units, and tuned mass dampers—to monitor its condition [85]. Sensors are deployed at critical structural locations, where they operate under command from a central server. After synchronization, each sensor node collects and processes structural data, which are transmitted back to the server for analysis. These data are then used to assess current structural performance and predict the remaining service life. The schematic workflow of wireless sensor application is illustrated in **Figure 5**.

5.2.1 Accelerometer

Accelerometers are among the most widely used sensors in SHM due to their cost-effectiveness, ease of installation, robustness, and suitability for both local and global monitoring applications. Their high sampling frequency capabilities make them ideal for capturing dynamic responses of structures [86]. For example, sampling rates above 1000 Hz enable precise dynamic analysis [87], provided the Nyquist theorem is satisfied: $F_s \geq 2F_o$, where F_s is the sampling frequency and F_o is the monitored frequency [88]. Accelerometers are largely unaffected by external environmental conditions, offering reliable and accurate structural performance data [89]. The ETNA high-dynamic-range accelerometer is a commonly used model, featuring a 108 dB dynamic range, 18-bit resolution, 0.5 msec timing accuracy, and integrated alerting and diagnostics systems. Wireless MEMS-based accelerometers have also gained popularity, categorized as single-hop or multi-hop systems [90]. Although accelerometers provide valuable data, integrating them with other systems like GPS can mitigate minor errors introduced during numerical integration [87]. For instance, 84 accelerometer channels, each costing approximately \$15,000, were installed on the Bill Emerson Memorial Bridge for comprehensive monitoring [83]. Accelerometers

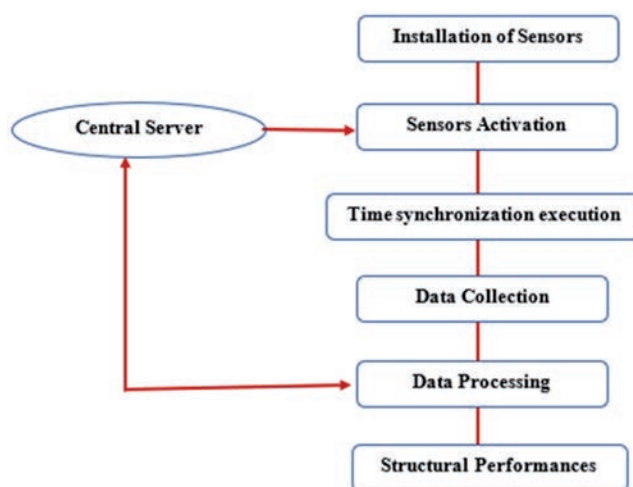


Figure 5.
The schematic approach of wireless sensors application.

have also been widely used in earthquake and wind-load monitoring, providing critical insights into structural responses [91].

5.2.2 Global positioning system (GPS)

GPS receiver is also implemented in SHM applications for civil engineering structures, making GPS an advanced tool for monitoring system [92–97]. GPS technology enhances SHM by enabling direct displacement measurements and tracking dynamic, static, and semi-static movements without requiring acceleration integration [92]. GPS sensors provide autonomous operation, high accuracy, and do not require line-of-sight between receivers. Sampling rates typically range from 50 Hz to 100 Hz [98].

Geodetic-grade GPS units have been successfully integrated with accelerometers in SHM studies [92, 94–97]. Researchers have also explored embedding these sensors into smartphones for cost-effective monitoring [99]. However, GPS accuracy can be affected by atmospheric interference and multipath effects. Signal processing techniques can mitigate these issues.

5.2.3 Smartphones

Modern smartphones, equipped with sensors such as gyroscopes, accelerometers, and magnetometers, are increasingly used in SHM due to their portability, affordability, and ease of use [99]. Studies have validated the embedded accelerometers for structural monitoring, demonstrating performance comparable to commercial sensors [100]. Despite their potential, challenges such as structural attachment, data preprocessing, and battery limitations must be addressed [99, 101]. For example, the Samsung Galaxy was employed as an SHM device, utilizing its onboard LSM6DSL accelerometer and an analyzer app to collect time-series data [99]. Smartphones have also been applied to bridge monitoring, cable force measurement, and seismic response validation [102, 103].

5.2.4 Acoustic emission (AE)

Among non-destructive testing methods, acoustic emission (AE) is a prominent technique for real-time monitoring of highway and bridge structures. Unlike other NDT methods used before or after loading, AE operates during loading by detecting stress waves generated from internal structural changes [104]. AE systems consist of a stress-wave source, sensor (transducer), and data processing unit. Emissions are categorized as primary (from the structure) or secondary (external noise) sources [105, 106]. Wireless AE systems, enhanced by MEMS technology, reduce installation costs and improve data acquisition [107]. AE has been successfully used for laboratory tests and in-situ evaluations of concrete and steel structures [108]. AE-based systems have also been applied to monitor wire breaks in bridge cables [109].

5.2.5 Linear variable displacement transducer (LVDT)

LVDTs are traditional sensors used for direct displacement measurements and are often mounted between fixed points on structures to track relative motion [110]. They are well-suited for long-term monitoring of structural deformation and crack opening due to their excellent stability [111]. This is the reason while they are suitable for measuring long-term degradation of structure crack opening displacement LVDTs have been used to validate other displacement monitoring methods [112]. A notable

example is the Kishwaukee River Bridge, where seven LVDT sensors have been tracking shear crack displacement since 2001 [113].

6. Optical fiber sensors in SHM

Optical Fiber Sensors (OFS) are increasingly adopted in SHM due to their high precision, electromagnetic immunity, corrosion resistance, durability, and compatibility with harsh environments. OFS is known to be one fast-developing technology and most assuring research area in both short-term and long-term structural health monitoring of civil engineering infrastructures due to their outstanding features of stability, durability, compatibility, and insensitivity to external electromagnetic agitations and corrosion [114–119]. Unlike traditional sensors (e.g., accelerometers), OFS offers distributed, quasi-distributed, and point sensing over long distances, making them well-suited for global strain mapping and damage detection in civil infrastructures [120]. While conventional sensors provide discrete data at limited locations, OFS offers thousands of sensing points along a single fiber, allowing continuous, distributed measurements that capture the comprehensive structural state. Through light scattering techniques, OFS can measure temperature, strain, and vibration across large-scale infrastructures in real time. Extensive research has documented the effectiveness and versatility of OFS in both the general field of sensing [121–124] and their specific applications in civil engineering [37, 38, 125–127]. These capabilities make OFS a superior choice for structural damage detection and comprehensive infrastructure health assessment.

OFS operates by converting structural changes—such as strain or temperature—into modulated light signals within optical fibers made of silica or polymers. An OFS system is a typical cylindrical structure made of 6 typical components which are light transmitters, a receiver, an optical fiber (the central core part), a modulator, and a signal processing unit. The optical fiber which is the core element in the OFS has a diameter ranging between 4 and 600 μm [128]. It is either made from silica glass or polymer materials, hence possessing a uniform reflective index that receives and transfers light from a source to its modulator component. For instance, a change in temperature or strain in a structure creates a respective expansion and contraction of the optical fiber. This change in length (contraction and expansion) of optical fiber is sent to the modulator which in turn controls the light and reflects it to the analytical or processing unit where the derivation of the current performance of the structure is produced [129].

Based on their applications, sensing technology, modulations, measurement points, etc. OFS can be classified into different groups. A brief discussion is presented for the three commonly adopted sensing-based devices which are grating-based sensors, Interferometric-based sensors, and the Distributed-based sensors are presented in the following section [130, 131].

6.1 Gratin-based sensor

One of the most adopted Gratin-based sensors is the Fiber Bragg Grating (FBG) Sensor. This system works in a way that the optical fiber of this type of FOS has various reflective indices. It operates according to the Bragg's law (white light beam written on the beams), at a wavelength, the Bragg wavelength is reflected when a beam of light from sources passes through the grating. This reflected Bragg wavelength (expressed in the equation below) is correlated to the grating period.

$$\lambda_B = 2n_{eff}\Lambda, \quad (2)$$

Where n_{eff} is the effective refractive index of the waveguide and Λ is the grating period.

In the presence of a change in strain and temperature from measurement, this λ_B shift and Λ is changed. Then the overall Bragg wavelength can be expressed as:

$$\Delta\lambda_B = \lambda_B \{ (\alpha + \xi) \Delta T + (1 - p_e) \Delta \epsilon \}. \quad (3)$$

Where $\Delta \epsilon$ is the change in strain, ΔT is the change in temperature, α is the thermal expansion coefficient, ξ is the coefficient of strain-optic, and p_e is the thermo-optic coefficient.

This system is well known and widely employed for civil engineering structural monitoring providing structural conditions using a varied refractive index [132–136]. A measurement principle of FBG sensor on civil structures is presented in **Figure 6**. Another form of Grating-Based sensors are Long Period Grating Sensors and Tilted Fiber Bragg Grating Sensors.

6.2 Interferometric sensors

This form of optic sensor has been adopted and the most common type on Interferometric is the Extrinsic Fabry-Perot Interferometric sensors (EFPI). The EFPI sensor is made of two optical sensors and a reflective fiber (also with hollow-core fiber). The former is performing as the input and output path in which light passes through them to the sensing part, then to the modulation while the former creates an air cavity called a Fabry-Perot cavity. During application, reflections are generated at both fibers' ends. R_1 and R_2 are the reference and sensing reflection respectively. The reference reflection, R_1 is a strain or temperature-dependent while R_2 depends on the cavity length. When R_1 and R_2 interfere, a sinusoidal (sine curve) signal is generated as the output. Based on the output signals, and the modulation of cavity length (Δl , the EFPI can be employed to measure an applied strain or temperature (perturbation). The expression below shows an example of measured strain on a structure.

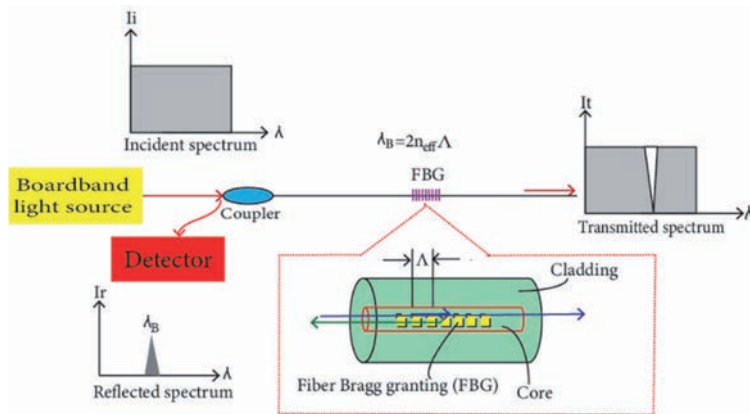


Figure 6. FBG sensor measurement principle (Image recreated from Ref. [37]).

Another form of this sensor system is SOFO, Mach-Zehnder, Sagnac, and Intensity/Micro bending Interferometric Sensor.

$$\varepsilon = \frac{\Delta l(\text{air gap})}{L} \quad (4)$$

6.3 Distributed fiber optic sensor (DFOS)

Compared to other forms of FOS, DFOS is cost-effective and can continuously monitor structure in real-time. This is sole because it only requires a single connection cable along with the optical fiber which measures the variation of one-dimensional structural in a distributed way. In the DOFS application, the perturbation changes (such as stain and temperature changes) are transferred to the optical fiber embedded inside or surface-bonded to the structure and modulated by the scattered (light and optical medium interaction signal in the fiber. The signal from this modulation is measured and the DFOS is achieved [120]. DOGS depends on different principles and techniques, in which the most adopted techniques form practice is the optical time-domain reflectometry (OTDR). OTDR simply works by detecting interacted position according to the propagation time as the light pulse (with a specific wavelength) propagates along with the optical fiber [137, 138]. The Brillouin optical time-domain reflectometer (BOTDR) and Raman are the two common DFOS based on Brillouin and Raman scattering.

6.4 Applications of OFS in civil structures

6.4.1 Bridges highway

One of the essential structures in transportation engineering is bridges and the structural monitoring of bridges has been a major concern around the world to increase their serviceability. The ability to continually monitor the operational loadings, structural performance, damage detection, environmental effect on bridge structure in real-time could be achieved by using optical fiber sensing technology. The FOS has served as an advance tool for monitoring various structural components (such as cables, deck, girders, piles, piers, abutment, etc.) and distress (such as stain, temperature, stress, deflection, corrosion, cracks, etc.) during the entire life cycle of the bridge (construction, operation, maintenance). From the literature, the application of FOS to monitor and estimate the structural condition and performance condition assessment [37]. The application of optical fiber sensors in the integrated bridge monitoring system during construction and post-construction; in the rehabilitated bridge; also, in the monitoring of bridge cables and suspenders have been deployed across the world as shown in **Table 3**.

6.4.2 Other form of civil infrastructures

Other essential structures in transportation engineering where the fiber optical sensing is utilized are in building stricture, tunnel and pipeline; railway structures, and geotechnical and foundations structures. The ability to continually monitor the operational loadings, structural performance, damage detection, environmental effect on these civil engineering infrastructures in real-time could be achieved by using optical fiber sensing technology. Similar to bridge application, the FOS also

Application of FOS	Country	Application of Fiber Optic Sensor (FOS)	References
The integrated bridge monitoring system	USA	Incorporation of remote monitoring approach based on FOS during construction stage for structural performance evaluation condition assessment of bridge in Florida	[139]
		simulated Brillouin (distributed) scattering based on local deformation algorithm and sensor measurand mechanism to monitor bridges	[140, 141]
		Employed FBG-based accelerometer based on stiffness to carry out a vibration test on a bridge	[142, 143]
	Canada	With different combinations of FOS, more than 15 bridges were instrumented with long-term structural health monitoring by the ISIS	[144]
	UK	The composite bridge was monitored using FBG sensors. Deployed FOS for monitoring strain and structural assessment of a 50-year-old concrete bridge Application of FBG-based sensor on an arch bridge for strain and full temperature monitoring	[145–147]
	China	Integration of the BOTDA system on a mainland bridge for strain monitoring and condition assessment.	[148–150]
	Korea	Monitoring of structural deflection of prestressed concrete bridges using a long-gauge FOS	[148, 151]
	Switzerland	Structural stability and reliability of FBG-based sensing through monitoring during the construction of a stay cable bridge for half a year was investigated.	[152, 153]
	Portugal	Estimated the displacement or distortion, strain, temperature changes of FBG-based sensing through the monitoring of concrete and steel bridges.	[154–156]
Monitoring of Rehabilitated bridge structures	Portugal	Application of various FOS has been employed on aged, deteriorated bridges for maintenance evaluation and repairs. Application of FBG-based sensing system on 100 years old steel bridge	[157, 158]
	USA	Local and global monitoring of strengthened bridges structures was investigated through the application of FOS	[159]
	China	Application of FBG and BOTDR for maintaining a rehabilitated concrete girder bridges and on strengthened T-beam	[160].
Bridge cables and suspenders	China	In China, The FOS was applied to evaluate various fatigue damaged bridge monitored a cable force using distributed BOTDA sensing techniques and high-precision FBG sensors. Li et al. monitored a glass fiber reinforced polymer (GFRP) bar by employing a smart stay cable built with FBG-based strain and temperature sensors.	[161–164]

Table 3.
A review of FOS applications in bridge structures.

serves as an advanced tool for monitoring various structural components during the entire life cycle of the structure (construction, operation, maintenance). **Table 4** below illustrates the application of FOS on other structures.

Application of FOS	Application of Fiber Optic Sensor (FOS)	References
Building For safety condition monitoring (both during construction, or in-service)	Bastianini et al. monitored the strain and cracks distresses around historical building structures by employing embedded optical fiber Brillouin sensors. Through the employment of FBG based biaxial accelerometer, Antunes et al., monitored a reinforced concrete water reservoir and a slender metallic telecommunication tower. Ni et al., deployed the FBG sensor to monitor the strain and temperature changes of the Canton Tower in China. During construction, Li et al., also performed FBG monitoring techniques on an 18-floor building. By monitoring the temperature and strain at three stages of each floor construction (i.e. before concrete pouring, during concrete pouring and after pouring)	[165–168]
Tunnel and Pipelines	Ye et al., deployed the use of FBG sensors to monitor the safety of a tunnel construction (i.e the temperature and strain) Metje et al., monitor the displacement/deflection (both lateral and rotational movement) of a tunnel lining using the new fiber optical sensing. Also, during backfilling and traffic-operating periods, Li et al., used a differential FBG strain sensor for monitoring the tunnel stability For pipelines, Glisic and Yao develop a real-time assessment of buried pipeline health conditions using distributed FOS. With the right support of the Brillouin spectrum strengthened with carbon-coated fibers and excellent communication fibers, Zhang et al., determined the locations of buckling and also predicted a progressive sequence of a pipe buckling.	[169–172]
Railway Infrastructures	Recently, the use of FOS as now being blooming in the area of railway structures. Yan et al., monitored various high-speed railway systems using strain and axle-counting measurement of the FBG-based method. In the Hong Kong transit railway, Wei et al., employed the FBG sensors on rail tracks. This assisted in generating an effective condition index reflecting the wheel situation and produced a track strains on rail-wheel contact. The FBG-based was also employed to monitor the Spanish high-speed line by Filograno et al. This examined the train wheels, dynamic loads, strain train identification, axle counting, speed, and acceleration detection. Bocciolone et al. also employed the FBG sensor to monitor the contact force and the vertical acceleration of the pantograph head in the underground pantograph-catenary system. Boffi et al. also used this method. Other authors that deployed the optic sensor are Pimentel et al., monitoring the train speed, acceleration, and weight distribution in Portugal.	[172–177]
Geotechnical Structures	In the geotechnical and soil stability field, Pei et al. monitored the lateral displacement of slopes in China using the FBG-based method. Lu et al. also employed the BOTDR-based optical fiber sensing method to monitor the stress and strain in precast pile.	[178, 179]

Table 4.
A review of FOS application in other civil engineering structures.

7. Conclusion

The monitoring and maintenance of civil infrastructure have emerged as critical topics in both the engineering community and national discourse, particularly in light of aging infrastructure across the United States. As reported by ASCE, many infrastructure systems have exceeded their intended service life, underscoring the urgent need for sustainable rehabilitation, resilience enhancement, and long-term maintenance. Ensuring the safety and reliability of civil structures is essential for public well-being. To address the limitations of conventional visual inspections, SHM has been widely adopted. This chapter has provided a comprehensive overview of SHM technologies, with an emphasis on their application to both existing and newly constructed infrastructure. Special attention was given to the integration of wireless smart sensors as a cost-effective alternative to traditional wired systems. Technologies such as accelerometers, GPS, LVDTs, and especially OFS have demonstrated significant promise in capturing the real-time behavior and performance of bridges, highways, tunnels, buildings, and geotechnical systems. The chapter also highlighted the advantages of OFS including their capacity for distributed, high-resolution measurements and explored their current application in advancing infrastructure diagnostics and service life extension. Collectively, these developments signal a shift toward intelligent, data-driven infrastructure management.

Despite the growing adoption of wireless sensor networks (WSNs), several technological limitations remain—particularly for long-term and large-scale SHM applications. These include challenges related to power supply longevity, data transmission reliability, bandwidth constraints, and large-volume data processing and storage. Additionally, the bespoke design of wireless hardware and software often demands significant expertise, making widespread implementation a challenge for many transportation agencies. To overcome these barriers, future research should focus on developing robust, scalable wireless sensing systems tailored for long-duration, multi-parameter monitoring. Continued efforts are also needed to integrate SHM systems within the broader framework of the Internet of Things (IoT), addressing key concerns such as cybersecurity, energy efficiency, edge/cloud computing integration, and real-time visualization. Another transformative avenue is the application of artificial intelligence (AI) in SHM. AI-driven platforms can enhance data interpretation, automate anomaly detection, and support predictive maintenance. Advanced machine learning models, agent-based systems, and intelligent data visualization tools will be essential in translating complex sensor data into actionable insights. The convergence of AI, IoT, and advanced sensing technologies holds immense potential to enable smart, resilient, and adaptive infrastructure systems. In summary, realizing the full potential of SHM for next-generation infrastructure will require interdisciplinary collaboration among academia, industry, and government agencies. With continued innovation and strategic investment, SHM can play a pivotal role in ensuring the sustainability and safety of global civil infrastructure networks.

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References

- [1] Esmaeili B, Parker PJ, Hart SD, Mayer BK, Klosky L, Penn MR. Inclusion of an introduction to Infrastructure course in a civil and environmental engineering curriculum. *Journal of Professional Issues in Engineering Education and Practice*. 2017;**143**:4016020
- [2] Norouzi M, Chàfer M, Cabeza LF, Jiménez L, Boer D. Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering*. 2021;**44**:1-18. DOI: 10.1016/j.jobbe.2021.102704
- [3] Kang S, Park S, Seo J. An alternative way to determine overall performance of Infrastructure—A case study of Korean Infrastructure facilities. *KSCE Journal of Civil Engineering*. 2019;**23**:1466-1472
- [4] Aschauer DA. Why is infrastructure important? In: Conference Series; [Proceedings]. Boston, MA: Federal Reserve Bank of Boston; 1990. pp. 21-68
- [5] Sun Z, Xing J, Tang P, Cooke NJ, Boring RL. Human reliability for safe and efficient civil infrastructure operation and maintenance – A review. *Developments in the Built Environment*. 2020;**4**:1-14. DOI: 10.1016/j.dibe.2020.100028
- [6] Cutter SL, Boruff BJ, Shirley WL. Social vulnerability to environmental hazards. *Social Science Quarterly*. 2003;**84**:242-261
- [7] Usman T, Fu L, Miranda-Moreno LF. Quantifying safety benefit of winter road maintenance: Accident frequency modeling. *Accident; Analysis and Prevention*. 2010;**42**:1878-1887
- [8] Usman T, Fu L, Miranda-Moreno LF. A disaggregate model for quantifying the safety effects of winter road maintenance activities at an operational level. *Accident; Analysis and Prevention*. 2012;**48**:368-378
- [9] Wanvik PO. Effects of road lighting: An analysis based on Dutch accident statistics 1987-2006. *Accident; Analysis and Prevention*. 2009;**41**:123-128
- [10] Ahmed SK, Mohammed MG, Abdulqadir SO, El-Kader RGA, El-Shall NA, Chandran D, et al. Road traffic accidental injuries and deaths: A neglected global health issue. *Health Science Reports*. 2023;**6**:1-6. DOI: 10.1002/hsr2.1240
- [11] American Society of Civil Engineers. 2025 Report Card for America's Infrastructure: A Comprehensive Assessment of America's Infrastructure. Reston, VA: American Society of Civil Engineers; 2025. Available from: www.infrastructurereportcard.org
- [12] American Society of Civil Engineers. 2021 Report Card for America's Infrastructure: A Comprehensive Assessment of America's Infrastructure. Reston, VA: American Society of Civil Engineers; 2021. Available from: www.infrastructurereportcard.org
- [13] American Society of Civil Engineers. 2017 Report Card for America's Infrastructure: A Comprehensive Assessment of America's Infrastructure. Reston, VA: American Society of Civil Engineers. Available from: www.infrastructurereportcard.org; 2017 [Accessed: July 5, 2025]
- [14] N.C. on P.W.I. (US). Fragile Foundations: A Report on America's Public Works: Final Report to the

President and the Congress. Washington, D.C: The Council; 1988

[15] Badgley et al. A Comprehensive Assessment of America's Infrastructure - Executive Summary. Reston, VA: American Society of Civil Engineers (ASCE); 2017

[16] Yates A. 2010 Victoria Infrastructure Report Card. Barton, ACT: Engineer Australia; 2010. p. iv

[17] Félío G. Canadian Infrastructure Report Card Volume 1: 2012: Municipal Roads and Water Systems. Ottawa, Ontario; 2017

[18] Infrastructure C. Canadian Infrastructure Report Card-Informing the Future. Ottawa, ON: C. Infrastructure; 2016

[19] Australia E. Infrastructure Report Card 2010: Victoria, Engineers Australia, Victorian Division. Barton, ACT: E. Australia; 2010

[20] Martin P, Rogers CA. Industrial location and public infrastructure. *Journal of International Economics*. 1995;39:335-351

[21] Betti R. Aging Infrastructure: Issues, Research, and Technology, Buildings and Infrastructure Protection. Washington, D.C: Homeland Security Science and Technology; 2010

[22] Rusnak CR. Sustainable strategies for concrete Infrastructure preservation: A comprehensive review and perspective. *Infrastructures (Basel)*. 2025;10:1-22. DOI: 10.3390/infrastructures10040099

[23] Cimellaro GP, Reinhorn AM, Bruneau M. Framework for analytical quantification of disaster resilience. *Engineering Structures*. 2010;32:3639-3649

[24] Roohi M, Ghasemi S, Sediek O, Jeon H, van de Lindt JW, Shields M, et al. Multi-disciplinary seismic resilience modeling for developing mitigation policies and recovery planning. *Resilient Cities and Structures*. 2024;3:66-84. DOI: 10.1016/j.rcns.2024.07.003

[25] Cha YJ, Ali R, Lewis J, Büyüköztürk O. Deep learning-based structural health monitoring. *Automation in Construction*. 2024;161:1-38. DOI: 10.1016/j.autcon.2024.105328

[26] Board NTS. Highway Accident Report Ceiling Collapse in the Interstate 90 Connector Tunnel Boston, Massachusetts July 10, 2006, Report. Washington: National Transportation Safety Board; 2007

[27] Nagarajaiah S, Erazo K. Structural monitoring and identification of civil infrastructure in the United States. *Structural Monitoring and Maintenance*. 2016;3:51-69

[28] Chang PC, Flatau A, Liu SC. Health monitoring of civil infrastructure. *Structural Health Monitoring*. 2003;2:257-267

[29] Farrar CR, Worden K. Structural Health Monitoring: A Machine Learning Perspective. Chichester, West Sussex: John Wiley & Sons; 2012

[30] Zhang Y, Chow CL, Lau D. Artificial intelligence-enhanced non-destructive defect detection for civil infrastructure. *Automation in Construction*. 2025;171:1-16. DOI: 10.1016/j.autcon.2025.105996

[31] Kudva JN, Marantidis C, Gentry JD, Blazic E. Smart structures concepts for aircraft structural health monitoring. In: *Smart Structures and Materials 1993: Smart Structures and Intelligent Systems*. Bellingham, WA: International

Society for Optics and Photonics; 1993. pp. 964-971

[32] Sohn H, Farrar CR, Hemez FM, Shunk DD, Stinemates DW, Nadler BR, et al. A Review of Structural Health Monitoring Literature: 1996-2001. USA: Los Alamos National Laboratory; 2003. pp. 1-7

[33] Giurgiutiu V, Rogers CA. Recent advancements in the electromechanical (E/M) impedance method for structural health monitoring and NDE. In: Smart Structures and Materials 1998: Smart Structures and Integrated Systems. Bellingham, WA: International Society for Optics and Photonics; 1998. pp. 536-547

[34] Lynch JP, Loh KJ. A summary review of wireless sensors and sensor networks for structural health monitoring. Shock and Vibration Digest. 2006;**38**:91-130

[35] Glisic B, Inaudi D, Casanova N. SHM process as perceived through 350 projects. In: Smart Sensor Phenomena, Technology, Networks, and Systems 2010. Bellingham, WA: International Society for Optics and Photonics; 2010. p. 76480P

[36] Rice JA, Mechitov K, Sim S-H, Nagayama T, Jang S, Kim R, et al. Flexible smart sensor framework for autonomous structural health monitoring. Smart Structures and Systems. 2010;**6**:423-438

[37] Ye XW, Su YH, Han JP. Structural health monitoring of civil infrastructure using optical fiber sensing technology: A comprehensive review. The Scientific World Journal. 2014;**2014**:1-11

[38] Rodriguez G, Casas JR, Villalba S. SHM by DOFS in civil engineering: A review. Structural Monitoring and Maintenance. 2015;**2**:357-382

[39] Hassani S, Dackermann U. A systematic review of advanced sensor technologies for non-destructive testing and structural health monitoring. Sensors. 2023;**23**:1-83. DOI: 10.3390/s23042204

[40] Karbhari VM. Health monitoring, damage prognosis and service-life prediction—Issues related to implementation. In: Sensing Issues in Civil Structural Health Monitoring. Dordrecht, The Netherlands: Springer; 2005. pp. 301-310

[41] Housner GW, Bergman LA, Caughey TK, Chassiakos AG, Claus RO, Masri SF, et al. Structural control: past, present, and future. Journal of Engineering Mechanics. 1997;**123**:897-971

[42] Djidrov M. Application of condition-based monitoring in enhancing mechanical system reliability and proactive structural damage detection. Technical Sciences. 2024;**27**:377-393. DOI: 10.31648/ts.10826

[43] Aktan AE, Catbas FN, Grimmelsman KA, Tsikos CJ. Issues in infrastructure health monitoring for management. Journal of Engineering Mechanics. 2000;**126**:711-724

[44] Catbas FN. Structural health monitoring: Applications and data analysis. In: Structural Health Monitoring of Civil Infrastructure Systems. Cambridge, UK: Elsevier; 2009. pp. 1-39

[45] Aktan AE, Ellingwood BR, Kehoe B. Performance-based engineering of constructed systems. Journal of Structural Engineering. 2007;**133**:311-323

[46] Hveem FN, Carmany RM. The factors underlying the rational design of

pavements. In: Highway Research Board Proceedings. Washington, D.C: Highway Research Board; 1949

[47] Isradi M, Prasetyo J, Aden TS, Rifai AI. Relationship of present serviceability index for flexible and rigid pavement in urban road damage assessment using pavement condition index and international roughness index. In: E3S Web of Conferences. Les Ulis, France: EDP Sciences; 2023. DOI: 10.1051/e3sconf/202342903012

[48] Fuentes L, Camargo R, Arellana J, Velosa C, Martinez G. Modelling pavement serviceability of urban roads using deterministic and probabilistic approaches. *International Journal of Pavement Engineering*. 2021;22:77-86. DOI: 10.1080/10298436.2019.1577422

[49] Catbas FN, Susoy M, Frangopol DM. Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data. *Engineering Structures*. 2008;30:2347-2359

[50] Zorzi S, Broccardo M, Tonelli D, Zonta D. Reliability-based metrics for structural health monitoring information quality assessment. *Structural Health Monitoring*. 2024;1-18. DOI: 10.1177/14759217241265956

[51] Gharehbaghi VR, Noroozinejad Farsangi E, Noori M, Yang TY, Li S, Nguyen A, et al. A critical review on structural health monitoring: Definitions, methods, and perspectives. *Archives of Computational Methods in Engineering*. 2022;29:2209-2235. DOI: 10.1007/s11831-021-09665-9

[52] Wang G, Ke J. Literature review on the structural health monitoring (SHM) of sustainable civil Infrastructure: An analysis of influencing factors in the

implementation. *Buildings*. 2024;14:1-42. DOI: 10.3390/buildings14020402

[53] Vijayan DS, Sivasuriyan A, Devarajan P, Krejsa M, Chalecki M, Żółtowski M, et al. Development of intelligent technologies in SHM on the innovative diagnosis in civil engineering—A comprehensive review. *Buildings*. 2023;13:1-22. DOI: 10.3390/buildings13081903

[54] Worden K, Bull LA, Gardner P, Gosliga J, Rogers TJ, Cross EJ, et al. A brief introduction to recent developments in population-based structural health monitoring. *Frontiers in Built Environment*. 2020;6:1-14. DOI: 10.3389/fbuil.2020.00146

[55] Entezami A, Sarmadi H, Behkamal B, Mariani S. Big data analytics and structural health monitoring: A statistical pattern recognition-based approach. *Sensors (Switzerland)*. 2020;20:1-17. DOI: 10.3390/s20082328

[56] Wang Q-A, Lu A-W, Ni Y-Q, Wang J-F, Ma Z-G. Bayesian network in structural health monitoring: Theoretical background and applications review. *Sensors*. 2025;25:3577. DOI: 10.3390/s25123577

[57] Webb A. *Statistical Pattern Recognition*. London: Arnold; 1999

[58] Jain AK, Duin RPW, Mao J. Statistical pattern recognition: A review. *IEEE Transactions on Pattern Analysis and Machine Intelligence*. 2000;22:4-37

[59] Mardanshahi A, Sreekumar A, Yang X, Barman SK, Chronopoulos D. Sensing techniques for structural health monitoring: A state-of-the-art review on performance criteria and new-generation technologies. *Sensors*. 2025;25:1-53. DOI: 10.3390/s25051424

- [60] Gul M, Necati Catbas F. Statistical pattern recognition for structural health monitoring using time series modeling: Theory and experimental verifications. *Mechanical Systems and Signal Processing*. 2009;**23**:2192-2204. DOI: 10.1016/j.ymssp.2009.02.013
- [61] Sohn H, Farrar CR, Hunter NF, Worden K. Structural health monitoring using statistical pattern recognition techniques. *The Journal of Dynamic Systems, Measurement, and Control*. 2001;**123**:706-711
- [62] Catbas FN, Aktan AE. Condition and damage assessment: Issues and some promising indices. *Journal of Structural Engineering*. 2002;**128**:1026-1036
- [63] Catbas FN, Brown DL, Aktan AE. Use of modal flexibility for damage detection and condition assessment: Case studies and demonstrations on large structures. *Journal of Structural Engineering*. 2006;**132**:1699-1712
- [64] K. Francoforte. Parameter Estimation Using Sensor Fusion and Model Updating. Orlando, FL: University of Central Florida; 2007
- [65] Bell ES, Sanayei M, Javdekar CN, Slavsky E. Multiresponse parameter estimation for finite-element model updating using nondestructive test data. *Journal of Structural Engineering*. 2007;**133**:1067-1079
- [66] Sanayei M, Bell ES, Javdekar CN, Edelmann JL, Slavsky E. Damage localization and finite-element model updating using multiresponse NDT data. *Journal of Bridge Engineering*. 2006;**11**:688-698
- [67] Farrar CR, Sohn H, Hemez FM, Anderson MC, Bement MT, Cornwell PJ, et al. Damage Prognosis: Current Status and Future Needs, Report. Los Alamos, NM, USA: Los Alamos National Laboratory; 2003
- [68] Zaurin R, Catbas FN. Computer vision oriented framework for structural health monitoring of bridges, IMAC XXV. Society for Experimental Mechanics. 2007:213-218
- [69] Celebi M. Seismic Instrumentation of Buildings (with Emphasis on Federal Buildings). University Park, PA: Citeseer; 2002
- [70] Wong K. Instrumentation and health monitoring of cable-supported bridges. *Structural Control and Health Monitoring*. 2004;**11**:91-124
- [71] Kurata N, Spencer BF Jr, Ruiz-Sandoval M. Risk monitoring of buildings with wireless sensor networks. *Structural Control and Health Monitoring*. 2005;**12**:315-327
- [72] Zhou G-D, Yi T-H. Recent developments on wireless sensor networks technology for bridge health monitoring. *Mathematical Problems in Engineering*. 2013;**2013**:1-33
- [73] Chae MJ, Yoo HS, Kim JY, Cho MY. Development of a wireless sensor network system for suspension bridge health monitoring. *Automation in Construction*. 2012;**21**:237-252
- [74] Nagayama T, Spencer BF Jr. Structural Health Monitoring Using Smart Sensors, Newmark Structural Engineering Laboratory. Urbana, IL: University of Illinois at Urbana ...; 2007
- [75] Straser EG, Kiremidjian AS, Meng TH. Modular, Wireless Damage Monitoring System for Structures. Stanford, CA: Stanford University; 2001. US6292108B1
- [76] Lynch JP, Law KH, Kiremidjian AS, Kenny TW, Carryer E, Partridge A.

The Design of a Wireless Sensing Unit for Structural Health Monitoring, in: Proceedings of the 3rd International Workshop on Structural Health Monitoring, CA: Stanford University Stanford; 2001. pp. 12-14

[77] Aoki S, Fujino Y, Abe M. Intelligent bridge maintenance system using MEMS and network technology. In: Smart Structures and Materials 2003: Smart Systems and Nondestructive Evaluation for Civil Infrastructures. Bellingham, WA: International Society for Optics and Photonics; 2003. pp. 37-42

[78] Chung H-C, Enomoto T, Shinozuka M, Chou P, Park C, Yokoi I, et al. Real time visualization of structural response with wireless MEMS sensors. In: Proceedings of 13th World Conference on Earthquake Engineering. Tokyo, Japan: International Association for Earthquake Engineering (IAEE); 2004. pp. 1-10

[79] Farrar CR, Allen DW, Park G, Ball S, Masquelier MP. Coupling sensing hardware with data interrogation software for structural health monitoring. Shock and Vibration. 2006;**13**:519-530

[80] Wang Y, Lynch JP, Law KH. Validation of an integrated network system for real-time wireless monitoring of civil structures. Ann Arbor. 2005;**1001**:48109

[81] Spencer BF Jr, Ruiz-Sandoval ME, Kurata N. Smart sensing technology: Opportunities and challenges. Structural Control and Health Monitoring. 2004;**11**:349-368

[82] Cho S, Yun C-B, Lynch JP, Zimmerman AT, Spencer BF Jr, Nagayama T. Smart wireless sensor technology for structural health

monitoring of civil structures. Steel Structures. 2008;**8**:267-275

[83] Jang S, Jo H, Cho S, Mechitov K, Rice JA, Sim S-H, et al. Structural health monitoring of a cable-stayed bridge using smart sensor technology: Deployment and evaluation. Smart Structures and Systems. 2010;**6**:439-459

[84] Li J. Structural Health Monitoring of an in-Service Highway Bridge with Uncertainties [Thesis]. USA: University of Connecticut; 2014

[85] Sumitomo S, Matsui Y, Kono M, Okamoto T, Fujii K. Long span bridge health monitoring system in Japan. In: Health Monitoring and Management of Civil Infrastructure Systems. Bellingham, WA: International Society for Optics and Photonics; 2001. pp. 517-524

[86] Gastineau A, Johnson T, Schultz A. Bridge Health Monitoring and Inspections—A Survey of Methods. USA: University of Minnesota; 2009

[87] Roberts GW, Meng X, Dodson AH. Integrating a global positioning system and accelerometers to monitor the deflection of bridges. Journal of Surveying Engineering. 2004;**130**:65-72

[88] Kaloop MR. Bridge safety monitoring based-GPS technique: Case study Zhujiang Huangpu bridge. Smart Structures and Systems. 2012;**9**:473-487

[89] Li X, Rizos C, Ge L, Tamura Y, Yoshida A. The complementary characteristics of GPS and accelerometer in monitoring structural deformation. In: Ion 2005 Meeting. Citeseer: Institute of Navigation (ION); 2005

[90] Sabato A, Niezrecki C, Fortino G. Wireless MEMS-based accelerometer sensor boards for structural vibration

monitoring: A review. *IEEE Sensors Journal*. 2016;**17**:226-235

[91] Celebi M. GPS in dynamic monitoring of long-period structures. *Soil Dynamics and Earthquake Engineering*. 2000;**20**:477-483

[92] Psimoulis P, Pytharouli S, Karambalis D, Stiros S. Potential of global positioning system (GPS) to measure frequencies of oscillations of engineering structures. *Journal of Sound and Vibration*. 2008;**318**:606-623

[93] Ashkenazi V, Roberts GW. Experimental monitoring of the Humber bridge using GPS. In: *Proceedings of the Institution of Civil Engineers-Civil Engineering*. London, UK: Thomas Telford-ICE Virtual Library; 1997. pp. 177-182

[94] Im SB, Hurlebaus S, Kang YJ. Summary review of GPS technology for structural health monitoring. *Journal of Structural Engineering*. 2013;**139**:1653-1664

[95] Kaloop MR, Li H. Monitoring of bridge deformation using GPS technique. *KSCE Journal of Civil Engineering*. 2009;**13**:423-431

[96] Xiong C, Niu Y. Investigation of the dynamic behavior of a super high-rise structure using RTK-GNSS technique. *KSCE Journal of Civil Engineering*. 2019;**23**:654-665

[97] Kaloop MR, Elbeltagi E, Hu JW, Elrefai A. Recent advances of structures monitoring and evaluation using GPS-time series monitoring systems: A review. *ISPRS International Journal of Geo-Information*. 2017;**6**:382

[98] Moschas F, Stiros S. Measurement of the dynamic displacements and of the modal frequencies of a short-span

pedestrian bridge using GPS and an accelerometer. *Engineering Structures*. 2011;**33**:10-17

[99] Guzman-Acevedo GM, Vazquez-Becerra GE, Millan-Almaraz JR, Rodriguez-Lozoya HE, Reyes-Salazar A, Gaxiola-Camacho JR, et al. GPS, accelerometer, and smartphone fused smart sensor for SHM on real-scale bridges. *Advances in Civil Engineering*. 2019;**2019**:1-15

[100] Dashti S, Bray JD, Reilly J, Glaser S, Bayen A, Mari E. Evaluating the reliability of phones as seismic monitoring instruments. *Earthquake Spectra*. 2014;**30**:721-742

[101] Feng M, Fukuda Y, Mizuta M, Ozer E. Citizen sensors for SHM: Use of accelerometer data from smartphones. *Sensors*. 2015;**15**:2980-2998

[102] Zhao X, Han R, Ding Y, Yu Y, Guan Q, Hu W, et al. Portable and convenient cable force measurement using smartphone. *Journal of Civil Structural Health Monitoring*. 2015;**5**:481-491

[103] Zhao X, Ri K, Han R, Yu Y, Li M, Ou J. Experimental research on quick structural health monitoring technique for bridges using smartphone. *Advances in Materials Science and Engineering*. 2016;**2016**:1-14

[104] Rens KL, Wipf TJ, Klaiber FW. Review of nondestructive evaluation techniques of civil infrastructure. *Journal of Performance of Constructed Facilities*. 1997;**11**:152-160

[105] Chowdhury FH, Raihan MT, Islam GMS. Application of different structural health monitoring system on bridges: An overview. In: *IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III*. Dhaka, Bangladesh: IABSE-BD; 2015. p. 10

- [106] Meo M. Acoustic emission sensors for assessing and monitoring civil infrastructures. In: *Sensor Technologies for Civil Infrastructures*. Cambridge, UK: Elsevier; 2014. pp. 159-178
- [107] Grosse C, Finck R, Kurz J, Reinhardt H. Monitoring techniques based on wireless AE sensors for large structures in civil engineering. In: *Proceedings of the EWGAE 2004 Symposium in Berlin*. University Park, PA: Citeseer; 2004. pp. 843-856
- [108] McLaskey GC, Glaser SD, Grosse CU. Beamforming array techniques for acoustic emission monitoring of large concrete structures. *Journal of Sound and Vibration*. 2010;**329**:2384-2394
- [109] Zejli H, Laksimi A, Tessier C, Gaillet L, Benmedakhene S. Detection of the Broken Wires in the Cables' Hidden Parts (Anchorings) by Acoustic Emission. Zurich, Switzerland: Advanced Materials Research (AMR) Trans Tech Publications Ltd; 2006. pp. 345-350
- [110] Yoder NC, Adams DE. Commonly used sensors for civil infrastructures and their associated algorithms. In: *Sensor Technologies for Civil Infrastructures*. Cambridge, UK: Elsevier; 2014. pp. 57-85
- [111] Dorafshan S, Maguire M. Bridge inspection: Human performance, unmanned aerial systems and automation. *Journal of Civil Structural Health Monitoring*. 2018;**8**:443-476
- [112] Park HS, Lee HM, Adeli H, Lee I. A new approach for health monitoring of structures: Terrestrial laser scanning. *Computer-Aided Civil and Infrastructure Engineering*. 2007;**22**:19-30
- [113] Wang M, Yim J. Monitoring of the I-39 Kishwaukee Bridge. USA: University of Illinois at Chicago; 2010
- [114] Nichols JM, Trickey ST, Seaver M, Moniz L. Use of fiber-optic strain sensors and holder exponents for detecting and localizing damage in an experimental plate structure. *Journal of Intelligent Material Systems and Structures*. 2007;**18**:51-67
- [115] Murayama H, Kageyama K, Uzawa K, Ohara K, Igawa H. Strain monitoring of a single-lap joint with embedded fiber-optic distributed sensors. *Structural Health Monitoring*. 2012;**11**:325-344
- [116] Silva-Muñoz RA, Lopez-Anido RA. Structural health monitoring of marine composite structural joints using embedded fiber Bragg grating strain sensors. *Composite Structures*. 2009;**89**:224-234
- [117] Pang C, Yu M, Gupta AK, Bryden KM. Investigation of smart multifunctional optical sensor platform and its application in optical sensor networks. *Smart Structures and Systems*. 2013;**12**:23-39
- [118] Khiat A, Lamarque F, Prella C, Pouille P, Leester-Schädel M, Büttgenbach S. Two-dimension fiber optic sensor for high-resolution and long-range linear measurements. *Sens Actuators A Physics*. 2010;**158**:43-50
- [119] Bao X, Chen L. Recent progress in distributed fiber optic sensors. *Sensors*. 2012;**12**:8601-8639
- [120] López-Higuera JM, Cobo LR, Incera AQ, Cobo A. Fiber optic sensors in structural health monitoring. *Journal of Lightwave Technology*. 2011;**29**:587-608
- [121] Udd E. An overview of fiber-optic sensors. *Review of Scientific Instruments*. 1995;**66**:4015-4030
- [122] Kersey AD. A review of recent developments in fiber optic sensor

technology. *Optical Fiber Technology*. 1996;**2**:291-317

[123] Grattan KTV, Sun T. Fiber optic sensor technology: An overview. *Sensors and Actuators A: Physical*. 2000;**82**:40-61

[124] Lee B. Review of the present status of optical fiber sensors. *Optical Fiber Technology*. 2003;**9**:57-79

[125] Leung CKY, Wan KT, Inaudi D, Bao X, Habel W, Zhou Z, et al. Optical fiber sensors for civil engineering applications. *Materials and Structures*. 2015;**48**:871-906

[126] Li H-N, Li D-S, Song G-B. Recent applications of fiber optic sensors to health monitoring in civil engineering. *Engineering Structures*. 2004;**26**:1647-1657

[127] Ferdinand P. The evolution of optical fiber sensors technologies during the 35 last years and their applications in structure health monitoring. In: *EWSHM – 7th European Workshop on Structural Health Monitoring*. Nantes, France; 2014

[128] Gupta BD. *Fiber Optic Sensors: Principles and Applications*. New Delhi, India: New India Publishing; 2006

[129] Li Q, Ansari F. High-strength concrete in triaxial compression by different sizes of specimens. *Materials Journal*. 2000;**97**:684-689

[130] Lee DC, Lee JJ, Kwon IB. Monitoring of fatigue crack growth in steel structures using intensity-based optical fiber sensors. *Journal of Intelligent Material Systems and Structures*. 2000;**11**:100-107

[131] Guo H, Xiao G, Mrad N, Yao J. Fiber optic sensors for structural health

monitoring of air platforms. *Sensors*. 2011;**11**:3687-3705

[132] Moyo P, Brownjohn JMW, Suresh R, Tjin SC. Development of fiber Bragg grating sensors for monitoring civil infrastructure. *Engineering Structures*. 2005;**27**:1828-1834

[133] Jacobs S, Matthys S, De Roeck G, Taerwe L, De Waele W, Degrieck J. Testing of a prestressed concrete girder to study the enhanced performance of monitoring by integrating optical fiber sensors. *Journal of Structural Engineering*. 2007;**133**:541-549

[134] Betz DC, Staudigel L, Trutzel MN, Kehlenbach M. Structural monitoring using fiber-optic Bragg grating sensors. *Structural Health Monitoring*. 2003;**2**:145-152

[135] Todd MD, Johnson GA, Vohra ST. Deployment of a fiber Bragg grating-based measurement system in a structural health monitoring application. *Smart Materials and Structures*. 2001;**10**:534

[136] Capoluongo P, Ambrosino C, Campopiano S, Cutolo A, Giordano M, Bovio I, et al. Modal analysis and damage detection by fiber Bragg grating sensors. *Sens Actuators A Physics*. 2007;**133**:415-424

[137] Güemes A, Fernández-López A, Soller B. Optical fiber distributed sensing-physical principles and applications. *Structural Health Monitoring*. 2010;**9**:233-245

[138] Zhu Z-W, Liu D-Y, Yuan Q-Y, Liu B, Liu J-C. A novel distributed optic fiber transducer for landslides monitoring. *Optics and Lasers in Engineering*. 2011;**49**:1019-1024

[139] Mehrani E, Ayoub A, Ayoub A. Evaluation of fiber optic sensors for

remote health monitoring of bridge structures. *Materials and Structures*. 2009;**42**:183-199

[140] Glisic B, Inaudi D. Development of method for in-service crack detection based on distributed fiber optic sensors. *Structural Health Monitoring*. 2012;**11**:161-171

[141] Mehrabi A, Khedmatgozar Dolati SS. Structural health monitoring and performance evaluation of bridges and structural elements. *Infrastructures (Basel)*. 2024;**9**:1-4. DOI: 10.3390/infrastructures9100178

[142] Talebinejad I, Fischer C, Ansari F. Serially multiplexed FBG accelerometer for structural health monitoring of bridges. *Smart Structures and Systems*. 2009;**5**:345-355

[143] Lu R, Judd J. Field-deployable fiber optic sensor system for structural health monitoring of steel girder highway bridges. *Infrastructures (Basel)*. 2022;**7**:1-15. DOI: 10.3390/infrastructures7020016

[144] Tennyson RC, Mufti AA, Rizkalla S, Tadros G, Benmokrane B. Structural health monitoring of innovative bridges in Canada with fiber optic sensors. *Smart Materials and Structures*. 2001;**10**:560

[145] Kister G, Badcock RA, Gebremichael YM, Boyle WJO, Grattan KTV, Fernando GF, et al. Monitoring of an all-composite bridge using Bragg grating sensors. *Construction and Building Materials*. 2007;**21**:1599-1604

[146] Surre F, Sun T, Grattan KT. Fiber optic strain monitoring for long-term evaluation of a concrete footbridge under extended test conditions. *IEEE Sensors Journal*. 2012;**13**:1036-1043

[147] Mokhtar MR, Owens K, Kwasny J, Taylor SE, Basheer PAM, Cleland D, et al. Fiber-optic strain sensor system with temperature compensation for arch bridge condition monitoring. *IEEE Sensors Journal*. 2011;**12**:1470-1476

[148] Chung W, Kim S, Kim N-S, Lee H. Deflection estimation of a full scale prestressed concrete girder using long-gauge fiber optic sensors. *Construction and Building Materials*. 2008;**22**:394-401

[149] He Z, Li W, Salehi H, Zhang H, Zhou H, Jiao P. Integrated structural health monitoring in bridge engineering. *Automation in Construction*. 2022;**136**:1-16. DOI: 10.1016/j.autcon.2022.104168

[150] Lv B, Peng Y, Du C, Tian Y, Wu J. Review of Brillouin distributed sensing for structural monitoring in transportation Infrastructure. *Infrastructures (Basel)*. 2025;**10**:148. DOI: 10.3390/infrastructures10060148

[151] Kim TM, Kim DH, Kim MK, Lim YM. Fiber Bragg grating-based long-gauge fiber optic sensor for monitoring of a 60 m full-scale prestressed concrete girder during lifting and loading. *Sens Actuators A Physics*. 2016;**252**:134-145. DOI: 10.1016/j.sna.2016.10.037

[152] Brönnimann R, Nellen PM, Sennhauser U. Application and reliability of a fiber optical surveillance system for a stay cable bridge. *Smart Materials and Structures*. 1998;**7**:229

[153] Bertola NJ, Henriques G, Brühwiler E. Assessment of the information gain of several monitoring techniques for bridge structural examination. *Journal of Civil Structural Health Monitoring*. 2023;**13**:983-1001. DOI: 10.1007/s13349-023-00685-6

[154] Barbosa C, Costa N, Ferreira LA, Araújo FM, Varum H, Costa A, et al.

Weldable fibre Bragg grating sensors for steel bridge monitoring. *Measurement Science and Technology*. 2008;**19**:125305

[155] Ietka I, Moutinho C, Pereira S, Cunha Á. Structural monitoring of a large-span arch bridge using customized sensors. *Sensors*. 2023;**23**:1-25. DOI: 10.3390/s23135971

[156] Rodrigues C, Cavadas F, Félix C, Figueiras J. FBG based strain monitoring in the rehabilitation of a centenary metallic bridge. *Engineering Structures*. 2012;**44**:281-290

[157] Rodrigues C, Félix C, Lage A, Figueiras J. Development of a long-term monitoring system based on FBG sensors applied to concrete bridges. *Engineering Structures*. 2010;**32**:1993-2002

[158] Costa BJA, Figueiras JA. Fiber optic based monitoring system applied to a centenary metallic arch bridge: Design and installation. *Engineering Structures*. 2012;**44**:271-280

[159] Jiang G, Dawood M, Peters K, Rizkalla S. Global and local fiber optic sensors for health monitoring of civil engineering infrastructure retrofit with FRP materials. *Structural Health Monitoring*. 2010;**9**:309-322

[160] Zhang W, Gao J, Shi B, Cui H, Zhu H. Health monitoring of rehabilitated concrete bridges using distributed optical fiber sensing. *Computer-Aided Civil and Infrastructure Engineering*. 2006;**21**:411-424

[161] Li D, Zhou Z, Ou J. Development and sensing properties study of FRP-FBG smart stay cable for bridge health monitoring applications. *Measurement*. 2011;**44**:722-729

[162] Li D, Zhou Z, Ou J. Dynamic behavior monitoring and damage

evaluation for arch bridge suspender using GFRP optical fiber Bragg grating sensors. *Optics and Laser Technology*. 2012;**44**:1031-1038

[163] He J, Zhou Z, Jinping O. Optic fiber sensor-based smart bridge cable with functionality of self-sensing. *Mechanical Systems and Signal Processing*. 2013;**35**:84-94

[164] Li H, Ou J, Zhou Z. Applications of optical fibre Bragg gratings sensing technology-based smart stay cables. *Optics and Lasers in Engineering*. 2009;**47**:1077-1084

[165] Bastianini F, Corradi M, Borri A, di Tommaso A. Retrofit and monitoring of an historical building using “smart” CFRP with embedded fibre optic Brillouin sensors. *Construction and Building Materials*. 2005;**19**:525-535

[166] Antunes P, Travanca R, Rodrigues H, Melo J, Jara J, Varum H, et al. Dynamic structural health monitoring of slender structures using optical sensors. *Sensors*. 2012;**12**:6629-6644

[167] Ni YQ, Xia Y, Liao WY, Ko JM. Technology innovation in developing the structural health monitoring system for Guangzhou new TV tower. *Structural Control and Health Monitoring*. 2009;**16**:73-98

[168] Li DS, Ren L, Li H-N, Song GB. Structural health monitoring of a tall building during construction with fiber Bragg grating sensors. *International Journal of Distributed Sensor Networks*. 2012;**8**:272190

[169] Glisic B, Yao Y. Fiber optic method for health assessment of pipelines subjected to earthquake-induced ground movement. *Structural Health Monitoring*. 2012;**11**:696-711

- [170] Metje N, Chapman DN, Rogers CDF, Henderson P, Beth M. An optical fiber sensor system for remote displacement monitoring of structures—Prototype tests in the laboratory. *Structural Health Monitoring*. 2008;**7**:51-63
- [171] Li C, Zhao Y-G, Liu H, Wan Z, Zhang C, Rong N. Monitoring second lining of tunnel with mounted fiber Bragg grating strain sensors. *Automation in Construction*. 2008;**17**:641-644
- [172] Zhang C, Bao X, Ozkan IF, Mohareb M, Ravet F, Du M, et al. Prediction of the pipe buckling by using broadening factor with distributed Brillouin fiber sensors. *Optical Fiber Technology*. 2008;**14**:109-113
- [173] Wei C, Cai Z, Tam H, Ho SL, Xin Q. Reliability verification of a FBG sensors based train wheel condition monitoring system. In: 2012 Second International Conference on Intelligent System Design and Engineering Application. Institute of Electrical and Electronics Engineers (IEEE); 2012. pp. 1091-1094
- [174] Corredera P, Rodríguez Barrios A, Martín-López S, Rodríguez-Plaza M, Andrés-Alguacil A, González-Herráez M. Real-Time Monitoring of Railway Traffic Using Fiber Bragg Grating Sensors. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers; 2012
- [175] Bocciolone M, Bucca G, Collina A, Comolli L. Pantograph–catenary monitoring by means of fibre Bragg grating sensors: Results from tests in an underground line. *Mechanical Systems and Signal Processing*. 2013;**41**:226-238
- [176] Boffi P, Cattaneo G, Amoriello L, Barberis A, Bucca G, Bocciolone MF, et al. Optical fiber sensors to measure collector performance in the pantograph–catenary interaction. *IEEE Sensors Journal*. 2009;**9**:635-640
- [177] Pimentel d RMCM, Barbosa MCB, Costa NMS, Ribeiro DRF, de Almeida Ferreira LA, Araújo FMM, et al. Hybrid fiber-optic/electrical measurement system for characterization of railway traffic and its effects on a short span bridge. *IEEE Sensors Journal*. 2008;**8**:1243-1249
- [178] Pei H-F, Yin J-H, Jin W. Development of novel optical fiber sensors for measuring tilts and displacements of geotechnical structures. *Measurement Science and Technology*. 2013;**24**:95202
- [179] Lu Y, Shi B, Wei GQ, Chen SE, Zhang D. Application of a distributed optical fiber sensing technique in monitoring the stress of precast piles. *Smart Materials and Structures*. 2012;**21**:115011

Assessment of Recycled Waste Materials for Engineering Applications in Turkey

Merve Akbas and Recep Iyisan

Abstract

This chapter evaluates the use of recycled waste materials in engineering applications within Turkey, focusing on sustainable construction practices and resource efficiency. It examines the physical and mechanical properties of recycled materials sourced from construction and demolition waste, along with urban debris, emphasizing their viability as substitutes for conventional construction materials in infrastructure projects. Key findings indicate that Recycled Concrete Aggregates (RCA) and Reclaimed Asphalt Pavement (RAP) exhibit comparable strength and durability to natural aggregates, particularly in road base and subbase applications. Laboratory tests demonstrate that RCA maintains over 90% of its original strength after freeze-thaw cycles, while RAP-treated base layers show improved rutting resistance and cost savings of up to 15% compared to traditional materials. Additionally, regulatory frameworks and quality control measures play a crucial role in successful implementation. Through comprehensive laboratory testing and real-world case studies, the chapter underscores the benefits and challenges of utilizing these materials, addressing critical factors such as durability, environmental impact, and material behavior. Furthermore, it explores the regulatory frameworks, quality control measures, and practical recommendations necessary for the successful implementation of recycled materials in engineering projects. By highlighting the potential for sustainable resource management and waste reduction, the findings aim to contribute to the development of eco-friendly engineering solutions and practices in Turkey.

Keywords: recycled waste materials, sustainable construction, Turkey, road engineering, environmental sustainability

1. Introduction

The global construction industry is a major contributor to environmental degradation, with significant amounts of Construction and Demolition Waste (CDW) generated annually. In Turkey, CDW accounts for a substantial portion of the total waste produced, reflecting the rapid pace of urbanization and infrastructure development. Estimates suggest that millions of tons of CDW are generated annually in Turkey, much of which ends up in landfills or unmanaged sites, exacerbating environmental and logistical challenges [1].

CDW management has emerged as a critical area of focus, especially as Turkey faces increasing pressure to align its construction sector with sustainable practices. Effective strategies, such as source-sorting and recycling, offer substantial environmental benefits by reducing waste sent to landfills and promoting material recovery. Moreover, initiatives like the establishment of Turkey's first CDW recycling plant have highlighted the practical potential for such efforts to minimize the environmental impacts. This facility has also inspired similar projects, particularly in urban transformation zones, to further advance recycling practices [2].

Building on these foundational initiatives, researchers began exploring innovative applications and strategies to enhance the use of recycled CDW. CDW management emerged from green supply chain integration, as discussed by Beldek et al. [3]. Their research demonstrated how collaborative partnerships among construction firms, recycling facilities, and municipal authorities could establish closed-loop systems for waste handling, optimizing resource efficiency and reducing environmental impacts. Yilmaz et al. [4] investigated CDW's application in underground mining operations, demonstrating the durability and strength of finely processed CDW when used in cemented paste backfill materials. This study also highlighted the massive volume of waste generated by the demolition of over 129,000 risky buildings under urban transformation projects. The growing awareness of such volumes spurred further research into alternative uses of CDW to reduce environmental burdens. Moreover, policy-driven strategies have been recognized as essential for scaling up CDW recycling efforts. Karademir and Ozbakir [1] stressed that stringent regulations, combined with industry incentives, could catalyze broader adoption of recycling practices, ultimately reducing environmental impacts and conserving natural resources. These policy recommendations remain crucial for sustaining long-term progress in CDW management.

Subsequent advancements included Beja et al. [5], who evaluated the use of recycled CDW aggregates in road construction. Their findings showcased that recycled materials could effectively replace natural aggregates, providing comparable performance under harsh conditions like heavy traffic and freeze-thaw cycles. These practical applications further solidified the viability of recycled CDW in various engineering domains. In parallel, researchers such as Bilgili and Çetinkaya [6] expanded the scope of inquiry with a life cycle assessment of earthquake-generated CDW management strategies. Their study emphasized the dual environmental and economic benefits of recycling earthquake debris, particularly in seismically active areas like İzmir and Istanbul. By reducing landfill reliance and minimizing environmental degradation, their work highlighted how recycled CDW could contribute significantly to urban resilience and sustainability.

This chapter aims to provide a comprehensive evaluation of recycled waste materials, specifically focusing on their engineering applications in Turkey. Building upon the existing body of research, it examines the physical, mechanical, and environmental properties of recycled materials sourced from CDW. The analysis encompasses their performance as unbound base and subbase layers in road and civil engineering projects, particularly under challenging conditions such as freeze-thaw cycles and heavy traffic loads. The regulatory framework and quality control measures required for the safe and effective implementation of these materials in Turkey's construction sector are also discussed, along with barriers and opportunities for widespread adoption. By synthesizing these findings, the chapter provides actionable insights for engineers, policymakers, and researchers. It highlights the potential for integrating recycled materials to promote sustainable construction practices, reduce

environmental impact, and advance Turkey's transition toward a circular economy. Ultimately, the chapter aspires to contribute to the development of eco-friendly engineering solutions and pave the way for the broader application of recycled waste materials in Turkey's construction industry.

2. Overview of construction and demolition waste (CDW) in Turkey

Construction and Demolition Waste (CDW) in Turkey is generated from a variety of sources, including urban transformation projects, infrastructure renewal, and disaster recovery efforts. Urban transformation, in particular, is a significant driver due to the ongoing replacement of unsafe and earthquake-prone buildings. It is estimated that Turkey generates millions of tons of CDW annually, accounting for approximately 30–40% of the total waste produced in urban areas. According to recent CDW data, Turkey has identified 701,710 risky independent units and 213,533 risky buildings, with 596,337 buildings demolished as part of these initiatives [7].

Urban transformation projects initiated by the Ministry of Environment, Urbanization, and Climate Change aim to address the country's high seismic vulnerability. Cities like Istanbul, Izmir, and Ankara generate substantial volumes of CDW due to large-scale demolitions of high-risk structures. For example, Istanbul Metropolitan Municipality [7] reported that urban transformation projects generate approximately 15% of the city's total waste annually. This includes not only demolition debris but also recyclable materials like concrete, steel, and bricks. A study by Kocak et al. [8] highlights that, nationwide, urban transformation accounts for over 25% of municipal solid waste in major cities. This underscores the importance of managing CDW sustainably to reduce the strain on landfills and mitigate environmental impacts. In addition to the waste generated through planned urban transformation, seismic activity serves as another major driver of CDW accumulation, often exacerbating existing waste management challenges. The February 2023 Kahramanmaraş earthquakes, for example, resulted in an estimated 60 million tons of debris, overwhelming local waste management infrastructure [9]. This seismic debris included hazardous materials such as asbestos and lead, complicating processing and disposal efforts. The scale of waste generated by such disasters underscores the critical need for robust disaster waste management systems that can effectively address both the immediate and long-term challenges posed by seismic events. These dual contributors—urban transformation and seismic activity—highlight the urgency of developing integrated and sustainable strategies for managing CDW in Turkey.

Urban transformation projects and seismic activity not only contribute significantly to the generation of CDW in Turkey but also underscore the urgent need for sustainable waste management strategies. While municipalities are starting to adopt innovative recycling practices, such as Istanbul Metropolitan Municipality's use of CDW for road construction, the current recycling rates remain insufficient. With less than 10% of CDW being recycled, the environmental and logistical challenges posed by landfilling and illegal dumping persist, emphasizing the necessity for systemic change.

Looking ahead, the interplay between urban transformation, population growth, and seismic activity further amplifies the urgency of addressing CDW management comprehensively. Projections indicate that CDW generation could reach 80–100 million tons annually by 2040, driven by Turkey's rising urbanization rate and ongoing large-scale transformations in major cities like Istanbul, Izmir, and Ankara.

If recycling rates remain stagnant, the country risks facing a critical shortage of landfill space as early as 2030, with urban centers bearing the brunt of these impacts. However, with strategic investments in recycling infrastructure, Turkey has the potential to significantly improve its recycling rate, achieving 30–40% by 2035. This advancement could reduce the annual waste requiring disposal by 20–30 million tons, alleviate pressure on landfills, conserve natural resources, and minimize environmental degradation. These challenges highlight the critical need for innovation and investment in sustainable waste management practices.

One promising avenue lies in the adoption of advanced recycling technologies, such as automated sorting systems and mobile crushing plants. By integrating these technologies into Turkey's waste management infrastructure, the nation could significantly enhance its capacity to process CDW effectively. By 2040, widespread implementation could facilitate the reuse of recycled materials in high-value applications, including asphalt production, road bases, and structural concrete. This shift would not only support environmental goals by reducing greenhouse gas emissions by 15–20% from the production of virgin materials but also offer economic advantages, potentially lowering material costs for the construction industry by up to 20%. Together, these advancements represent a pathway toward a more sustainable and economically resilient approach to CDW management in Turkey.

The effectiveness of these strategies depends not only on long-term advancements but also on robust seismic resilience planning. Turkey's high seismic vulnerability, particularly along the Marmara fault line, poses a significant challenge in terms of CDW management. For instance, a major earthquake, such as the expected Marmara fault rupture, could generate over 50 million tons of debris in a single event. Integrating post-disaster recycling systems into the broader waste management strategy could enable the recovery of 40–50% of this waste, transforming it into valuable materials for reconstruction within 6–12 months. This dual focus—advancing everyday recycling technologies and preparing for disaster scenarios—underscores the importance of a holistic approach to ensure sustainable growth and resilience in Turkey's construction sector.

To achieve these goals, policy and infrastructure development play a pivotal role. Introducing stricter regulations for CDW management, such as mandatory recycling targets and penalties for illegal dumping, is essential for enforcing sustainable practices. Simultaneously, establishing regional recycling hubs equipped with state-of-the-art processing technology will ensure the capacity to handle high volumes of waste. Complementing these structural changes, public awareness campaigns can promote understanding among contractors and the public about the economic and environmental benefits of recycling. Moreover, integrating circular economy principles into CDW management by encouraging the use of recycled materials through incentives and subsidies for public and private construction projects could further solidify Turkey's leadership in sustainable practices. These combined efforts pave the way for Turkey to not only address current challenges but also emerge as a regional leader in eco-friendly CDW management, setting an example for balancing economic development with environmental stewardship.

3. Engineering properties of CDW in Turkey

This section delves into the key materials derived from Construction and Demolition Waste (CDW) in Turkey and evaluates their properties for engineering

applications. Among the most commonly recycled materials are Recycled Concrete Aggregates (RCA), Recycled Asphalt Pavement (RAP), and bricks or masonry waste. Each of these materials offers unique characteristics and challenges, which influences their suitability for various construction applications such as road bases, pavement layers, and subbase materials. While this section provides an overview of CDW properties and previous studies, the research methods, experimental procedures, and analytical techniques applied in this study are detailed in Section 4 (Methodology and Proposed Applications). This section elaborates on the experimental approach, testing standards, and data analysis framework applied to assess the suitability of recycled waste materials in engineering projects in Turkey.

3.1 Recycled concrete aggregates (RCA)

Recycled Concrete Aggregates (RCA) have gained recognition in Turkey as sustainable alternatives to natural aggregates (NA) for various engineering applications. Studies, as summarized in **Table 1**, demonstrate that RCA offers mechanical properties comparable to NA while delivering environmental benefits such as reduced carbon emissions and resource conservation. These characteristics make RCA suitable for use in pavement layers, subbase materials, and highway drainage systems.

Beyond the broad sustainability advantages of RCA, a closer examination of its material-specific characteristics is essential to fully understand its engineering behavior—particularly when applied in structural or infrastructure contexts. Recycled Concrete Aggregate derived from construction and demolition waste exhibits distinct physical and mechanical properties that differ from those of natural aggregates and can influence overall performance. One of the defining features of RCA is the presence of adhered residual cement mortar on the aggregate surface. This residual layer contributes to increased porosity and higher water absorption, often exceeding 5%, which contrasts with the typical 1–2% absorption values observed in natural gravel. Additionally, RCA exhibits a higher Los Angeles (LA) abrasion loss, indicating its relatively lower resistance to fragmentation under mechanical stress when compared to pristine aggregates. Despite these limitations, multiple laboratory studies conducted in Turkey have demonstrated that when RCA is properly processed and sourced from quality concrete rubble, it can be used to produce new concrete mixes with compressive strengths well above 20 MPa. This performance level satisfies structural-grade requirements—for example, the C20/25 concrete class defined by TS EN 206 necessitates a characteristic compressive strength of 20 MPa at 28 days. While the elastic modulus of recycled aggregate concrete (RAC) tends to be 10–30% lower than that of conventional concrete, largely due to the compliant interfacial mortar zone, it remains within acceptable ranges for design applications when RCA replacement rates are moderate. Indeed, mixtures with up to 30% RCA replacement have shown minimal reduction in modulus for concrete grades around 30 MPa. Furthermore, RCA particles generally have a rough and angular morphology that enhances mechanical interlock and friction at the aggregate interfaces. This characteristic contributes positively in both unbound applications—by increasing the internal friction angle—and in concrete mixtures—by promoting better paste-aggregate bonding. As such, while raw RCA introduces certain performance trade-offs, these can be effectively mitigated through careful material selection, mix proportioning, and the use of supplementary techniques such as pre-soaking or surface treatments. When managed appropriately, RCA-based materials can deliver mechanical properties that meet national design standards and enable sustainable construction practices in Turkey.

Study	Focus	Key Findings	Applications
Ugurlu et al. [10]	Effect of binder content and RCA on freeze-thaw and sulfate resistance of geopolymer concretes.	Increasing binder content improved freeze-thaw and sulfate resistance. RCA usage led to slight strength loss but remained suitable for geopolymer concrete.	Durable concretes for harsh environments.
Akbas et al. [11]	Impact of freeze-thaw cycles on the stiffness of RCA as unbound base/subbase material.	RCA from Istanbul demonstrated suitable stiffness for unbound base/subbase use. Resilient modulus was the highest after 5 freeze-thaw cycles but declined with further cycles.	Pavement layers for extreme climates.
Bayraktar et al. [12]	Effects of cement dosage and waste tire rubber on foam concretes under H ₂ SO ₄ and freeze-thaw conditions.	Increased cement dosage significantly improved compressive strength. Foam concretes with silica fume and high cement content showed optimal resistance to freeze-thaw cycles, abrasion, and acid attack.	Lightweight, durable materials for industrial applications.
Akbas and İyisan [13]	Freeze-thaw effect on the stiffness properties of RCA in road embankments.	RCA showed resilience in cold conditions with minimal deformation after freeze-thaw cycles, proving its applicability in road construction.	Road embankments for cold climates.
Toka and Olgun [14]	Performance of RCA in granular road base and sub-base layers with varying ratios.	Optimal performance achieved by mixing 50% RCA with natural aggregates. RCA use in pure form showed high permeability but was less suitable compared to blended use.	Road base and sub-base for highways.
Bayraktar et al. [15]	Mechanical and durability characteristics of concrete with different treatments of recycled fine aggregates under MgSO ₄ and freeze-thaw cycles.	Washing treatments improved durability, with 20% washed RFA showing the best freeze-thaw resistance. Strength improved significantly with optimal RFA ratios.	Durable concretes for freeze-thaw regions.
Tarhan and Sahin [16]	Use of recycled aggregate concretes in road and site applications under freeze-thaw cycles.	RCA mixtures showed high resilience to freeze-thaw effects, proving effective for road and site concrete applications. The best results were achieved with specific blending ratios of RCA and NA.	Road and site concretes for harsh climates.
Toka and Olgun [17]	Mechanical and economic evaluation of RCA as granular road base and sub-base material.	About 50% RCA and 50% crushed aggregates provided optimal cost savings and performance for granular road base material, reducing costs by 13% compared to pure crushed aggregate.	Cost-effective highway construction materials.
Aytekin et al. [18]	Assessment of recycled waste materials for use in unbound pavement layers.	RCA mixed with crushed limestone showed excellent performance in road base and sub-base layers. RCA met Turkey Highways Technical Specifications (THTS) and provided better results in CBR and freeze-thaw resistance compared to natural aggregates.	Pavement layers for highways and rural roads.
Ulucan and Alyamac [19]	Mechanical and environmental properties of green concretes using RCA and supplementary cementitious materials.	RCA and silica fume significantly reduced environmental impact, including energy consumption and global warming potential. Suitable for sustainable construction, particularly in earthquake-prone areas.	Sustainable materials for green construction.

Table 1.
Overview of RCA studies conducted in Turkey.

In recent years, particularly after 2020, research interest in RCA has shifted toward more nuanced challenges related to long-term performance and environmental durability. Given Turkey's diverse climate, including regions subject to severe freeze-thaw cycles and seismic activity, the durability of RCA under such conditions has emerged as a key area of investigation. For instance, Ugurlu et al. [10] demonstrated enhanced durability of RCA-based geopolymer concretes when exposed to aggressive environmental conditions. Similarly, Akbas et al. [11] found that RCA exhibits strong resilience under repeated freeze-thaw cycles, reinforcing its potential for flexible pavement applications and road construction in extreme climates. Other studies, such as those by Bayraktar et al. [12] and Akbas and Iyisan [13], have highlighted RCA's suitability in producing lightweight and durable materials, especially for industrial or cold-climate applications. Laboratory studies evaluating RCA's freeze-thaw durability have produced critical insights. Freeze-thaw durability tests indicate that 100% RCA materials can suffer stiffness reductions if they become saturated and freeze. For example, in one study a base layer made entirely with RCA showed a resilient modulus decrease of about 53% after 20 freeze-thaw cycles. This loss is attributed to freeze expansion of water in the high-porosity mortar of RCA, causing micro-cracking and stiffness degradation. However, blended or treated RCA mixtures demonstrate much improved freeze-thaw performance. When RCA is mixed with natural aggregate or when lower replacement ratios are used, the reduction in stiffness is far less severe; in fact, some experiments show minimal change (or even slight increases) in resilient modulus after repeated freeze-thaw cycles. These results suggest that by limiting the RCA content or ensuring good drainage (to avoid saturation), base layers incorporating RCA can endure Eastern Turkey's harsh winters with durability comparable to natural aggregates. In concrete applications, the use of air-entraining admixtures (as per ASTM C260 recommendations) can greatly improve freeze-thaw resistance of RAC. Turkish standards (e.g., TS 500 and TS EN 206) emphasize a durability factor $> 90\%$ after 100 freeze-thaw cycles for concrete in exposure class XF2 (freeze-thaw with deicing). Air-entrained RAC mixes have achieved durability factors above 95%, nearly matching control concrete. Thus, with proper mix design (air entrainment, moderate RCA content, and low water/cement ratio), RAC can meet freeze-thaw durability requirements in Eastern Turkey.

In addition to durability, another critical consideration for RCA in Turkey is its structural performance under dynamic loading conditions—particularly seismic activity. Turkey's high seismicity (especially in the North Anatolian Fault region and Eastern Anatolia) demands that structural materials possess adequate ductility and strength retention under cyclic loads. Expanded studies on full-scale structural members made with RAC have shown encouraging results: Key seismic performance indicators such as ductility, energy dissipation, and stiffness degradation were found to be comparable between RAC and natural aggregate concrete members. In reversed cyclic loading tests on reinforced concrete columns, the use of RCA did not adversely affect drift capacity or hysteretic behavior. In fact, it was observed that columns and slabs with 100% RCA coarse aggregate exhibited similar failure modes and ductility to those with natural aggregates. This indicates that RCA can be safely used in structural concrete even in seismic zones, provided that mix design and quality control (e.g., achieving compressive strength ≥ 30 MPa and using modern seismic detailing per Turkish Earthquake Code 2018) are in place. Overall, the material-level analyses demonstrate that RCA's engineering properties—such as stiffness, strength, and durability—can be optimized to meet or improve upon the required standards, making it a viable material in Turkey's construction sector across various climates and loading conditions.

In parallel with technical performance, environmental and economic assessments have also supported the use of RCA in Turkey. For example, Toka and Olgun [17] reported that replacing 50% of NA with RCA led to a 13% cost reduction without compromising structural integrity. Aytekin et al. [18] further validated that RCA can meet the Turkish Highways Technical Specifications (THTS), enhancing its credibility for infrastructure applications. Collectively, these findings, detailed in **Table 1**, position RCA as a viable and cost-effective material for sustainable construction practices in Turkey. Complementing these insights, a growing body of literature has focused on RCA's durability under Turkey's climatic conditions—particularly where environmental extremes are present. One key concern is RCA's behavior under repeated freeze-thaw cycling. Laboratory investigations have shown that RCA base layers may experience a reduction in resilient modulus after 20 freeze-thaw cycles. However, this degradation can be significantly minimized by blending RCA with NA or by limiting its content in the mix—achieving over 90% strength retention after just 10 cycles. In concrete applications, the use of air-entraining admixtures has proven effective in preserving durability, enabling recycled aggregate concrete (RAC) to attain durability factors above 95%—approaching the performance levels of conventional concrete. Additionally, cyclic loading tests under seismic simulation have revealed that when mix design is optimized, RAC structural members can achieve ductility and energy dissipation capacity comparable to traditional concrete counterparts.

Overall, the evolution of RCA research in Turkey reflects a growing recognition of its potential to address both environmental and engineering challenges. From early studies establishing its basic mechanical properties to recent innovations in pre-treatment and application in diverse contexts, RCA has demonstrated consistent improvements in performance. These findings not only support the adoption of RCA in Turkish construction practices but also provide a framework for its integration into global sustainable construction strategies.

3.2 Recycled asphalt pavement (RAP)

The use of recycled asphalt pavement (RAP) and recycled concrete materials in construction has gained significant attention in Turkey due to increasing infrastructure demands and the need for sustainable practices. Recent studies, as summarized in **Table 2**, demonstrate RAP's adaptability, durability, and cost-effectiveness across diverse contexts.

Before examining these applications in detail, it is essential to consider the material-specific characteristics that govern RAP's engineering behavior, particularly within the context of Turkey's climatic and infrastructural conditions. RAP, obtained from milling or removing old asphalt layers, consists of aggregate coated with aged bituminous binder. This aged binder imparts a unique set of mechanical and chemical properties to RAP. For instance, RAP aggregates obtained from sources in Turkey typically exhibit a lower apparent specific gravity and higher residual bitumen content than virgin aggregates. Their effective specific gravity generally ranges between 2.3 and 2.5 due to the presence of aged asphalt binder, compared to approximately 2.6–2.7 for uncoated natural aggregates such as clean limestone. The bituminous coating enhances elasticity under load and offers water resistance. In terms of mechanical stiffness, RAP benefits from the viscoelastic behavior imparted by the aged asphalt binder, which exhibits higher viscosity and an elevated softening point relative to virgin binder. Consequently, asphalt mixtures incorporating RAP tend to demonstrate enhanced stiffness at service temperatures. This increased

Study	Focus	Key findings	Applications
Gul [20]	Effect of recycled cement concrete (RCC) content on rutting behavior of asphalt concrete.	Increased RCC content improved rutting resistance in asphalt.	Durable asphalt for rutting resistance.
Sengoz et al. [21]	Performance evaluation of warm mix asphalt mixtures with RAP.	Utilization of RAP with warm mix asphalt additives reduced emissions.	Sustainable warm mix asphalt pavements.
Seferoglu et al. [22]	Investigation of the effect of RAP material on permeability and bearing capacity in the base layer.	Increased RAP content reduced CBR values, but cement treatment improved bearing capacity.	Durable road base for infrastructure.
Seferoglu et al. [23]	Investigating the mechanical behavior of RAP bases in large-scale test box.	100% RAP with 3% cement showed suitable elastic deformation and permanent strain values.	High-load road base applications.
Abut and Yildirim [24]	Investigation of durability properties of RAP-containing roller compacted concrete pavement.	Using up to 20% RAP in roller-compacted concrete showed no significant reduction in freeze-thaw resistance.	Roller-compacted concrete applications
Fenerci et al. [25]	Economic potentials of RAP in urban road infrastructure: a case study from Yalova city.	Using RAP at 30, 50, and 70% reduced costs by 6, 11, and 15%, respectively.	Cost-effective urban road materials.
Kaya [26]	Usability of 100% RAP as a cold-patching material in Turkey.	100% RAP met durability criteria at conditioning temperatures above 22°C, with Marshall stability results exceeding specification limits.	Cold patching for road repairs.
Uygunoglu et al. [27]	Durability effect of reclaimed asphalt aggregate on concrete road pavement.	RAP at 25–50% replacement showed acceptable durability and corrosion resistance.	Durable concrete pavements for harsh conditions.
Dokuzlar et al. [28]	Effect of recycled asphalt waste on mechanical properties of alkali-activated mortars.	Alkali-activated mortars with recycled asphalt waste showed a compressive strength of 45.74 MPa.	Sustainable mortars with reduced cement usage.

Table 2.
Overview of RAP studies conducted in Turkey.

rigidity contributes positively to the load-bearing capacity of unbound base layers. Large-scale cyclic plate load tests conducted in Turkey have shown that 100% RAP base layers can achieve elastic modulus values in the range of 150 MPa, which is comparable to those observed in conventional granular base materials. Moreover, the partial substitution of RAP—typically at 20–30% by weight—in granular base courses has been shown to increase the composite resilient modulus, primarily due to the semi-cementitious behavior of the bitumen-coated aggregates. However, this stiffness enhancement introduces a trade-off in terms of fatigue performance. The aged binder, often equivalent in consistency to hard-penetration grades such as 20/30, exhibits reduced ductility and elasticity. As a result, high-RAP mixtures are more susceptible to fatigue-induced cracking under repeated traffic loading and thermal cycling, particularly at low temperatures. In the absence of binder modification or

rejuvenation strategies, these mixtures tend to exhibit diminished fatigue life and a higher propensity for cracking. Therefore, while the inclusion of RAP improves stiffness and rutting resistance, it necessitates appropriate binder adjustments—such as the incorporation of softening agents or rejuvenators—to restore the required flexibility and ensure long-term durability under cyclic and thermal loading conditions. However, the influence of these material properties is not uniform and can vary depending on the environmental conditions in which RAP is applied.

Turkey's geography encompasses both extremely hot climatic zones—such as the Southeastern Anatolia Region—and cold, mountainous areas like Eastern Anatolia. Given that the performance of RAP is temperature-sensitive, its suitability varies depending on regional climatic conditions and intended applications. In Southeastern Turkey, summer air temperatures frequently exceed 40°C, resulting in asphalt surface temperatures ranging from 50 to 60°C. Under such elevated conditions, rutting (i.e., permanent deformation) becomes a predominant concern in asphalt pavements. The use of RAP is advantageous in these environments due to the hardened nature of the aged bituminous binder, which possesses high viscosity and softening point at elevated temperatures. These properties restrict flow under load and enhance rutting resistance. For instance, Hamburg wheel tracking tests conducted on 50% RAP mixtures in Turkey (performed at 50°C per EN 12697-22 or AASHTO T324) demonstrated rut depths below 10 mm after 20,000 load cycles—well within the acceptable limits and superior to virgin mixtures. Field observations on highways in the Mediterranean and Southeastern regions corroborate these findings, showing that wearing courses incorporating RAP experience noticeably reduced rutting during peak summer periods. Conversely, in the continental climate of Eastern Turkey, where winter temperatures can drop to −30°C and pavements are exposed to repeated freeze-thaw cycles, performance concerns shift toward thermal cracking and material durability. In such cases, asphalt mixtures with high RAP content—particularly in surface layers—may exhibit increased brittleness and reduced flexibility, heightening the risk of thermal cracking due to the aged binder's inability to adequately dissipate thermal stresses. However, when RAP is utilized in unbound applications such as base or subbase layers, its cold-weather performance is generally favorable. The asphalt coating on RAP particles creates a hydrophobic layer, minimizing moisture retention and thereby reducing the potential for frost heave. Cyclic load tests on RAP bases conducted at low temperatures have shown modest increases in stiffness due to binder hardening, but without significant deterioration or cracking. These findings indicate that unbound RAP layers, when properly compacted and not fully saturated, can maintain mechanical stability through freeze-thaw cycles. These climate-driven performance characteristics have been increasingly reflected in empirical studies across Turkey, where researchers have investigated the applicability of RAP in diverse pavement structures and environmental conditions. Early studies, such as Gul [20], highlighted RAP's ability to maintain rutting resistance in asphalt mixtures, particularly in coarse-graded designs. Subsequent research, such as Seferoğlu et al. [22], demonstrated that cement-treated RAP significantly enhanced bearing capacity and reduced permeability, making it a viable option for heavy traffic and varied climatic conditions. Innovative uses of RAP, such as its application in cold patching [26] and integration into concrete road pavements [27], have further established its adaptability across urban and rural projects. These studies also emphasize its role in reducing construction costs and environmental impacts, with Fenerci et al. [25] reporting cost savings of up to 15% in urban infrastructure projects. RAP's versatility extends to sustainable construction materials, such as alkali-activated mortars, which exhibits improved strength and acid resistance [28].

In summary, the high stiffness, moderate load-bearing capacity, and low permeability of RAP make it particularly effective against rutting in hot climates and reasonably resilient in cold regions in Turkey when appropriately applied. Addressing the known limitations—primarily brittleness and fatigue sensitivity at low temperatures—through material-level interventions such as the incorporation of softer binder grades, rejuvenating agents, or polymer additives is crucial for ensuring reliable surface layer performance.

3.3 Recycled bricks, masonry, and other materials derived from CDW

The recycling of bricks, masonry waste, and other materials derived from CDW has become a critical focus in Turkey’s push toward sustainable construction practices. **Table 3** showcases Turkey’s progressive approach to recycling CDW, emphasizing innovations that enhance sustainability and material performance.

Early studies, such as Algin and Turgut [29], demonstrated the viability of incorporating cotton and limestone powder into lightweight and thermally efficient

Study	Focus	Key Findings	Applications
Algin and Turgut [29]	Use of cotton and limestone powder wastes in bricks	Cotton and limestone powder wastes were found to improve compressive strength and reduce unit weight, meeting international standards for construction.	Lightweight, thermally efficient construction materials.
Altuncu and Kasapseckin [30]	Management and recycling of constructional solid waste in Turkey	Differentiated solid waste materials like gypsum, ceramics, and metals were effectively managed, reducing environmental pollution.	Sustainable practices in urban redevelopment projects.
Bilgin et al. [31]	Use of waste marble powder in brick industry	Marble powder improved the physical, mechanical, and chemical properties of industrial bricks, enhancing compressive strength and thermal insulation.	Eco-friendly industrial brick production.
Atan et al. [32]	Combined effects of red mud and agricultural waste in bricks	Use of bauxite waste and agricultural residues reduced clay consumption and improved brick porosity, making them lightweight and sustainable.	Sustainable lightweight ceramic bricks.
Karslioglu et al. [33]	Insulation properties of bricks with waste rubber and plastic	Recycled rubber and plastic enhanced thermal and sound insulation properties while reducing reliance on non-renewable resources.	Thermally efficient and eco-friendly bricks.
Ulugol [34]	Effects of self-healing on CDW-based geopolymer composites	Self-healing capabilities in geopolymer composites improved durability, microstructure, and electrical properties.	Advanced geopolymer materials for construction.
Erdogmus et al. [35]	Recycling marble cutting waste in clay bricks	Marble cutting waste improved compressive strength and durability, particularly for finer particle sizes and optimized sintering conditions.	Durable and resource-efficient bricks.
Uysal et al. [36]	Use of waste marble, brick, and ceramic powders in geopolymer composites	Use of waste marble, brick, and ceramic powders in geopolymer composites	Sustainable geopolymer mortars and materials.

Table 3.
Summary of studies on recycled bricks and masonry waste in Turkey.

bricks. Building on this, Altuncu and Kasapşekkin [30] emphasized the potential of recycling gypsum, ceramics, and metals for reducing environmental pollution and supporting urban redevelopment. Advancements in recycling practices have explored industrial and agricultural by-products. For instance, Bilgin et al. [31] utilized waste marble powder to enhance the compressive strength and thermal insulation of bricks, while Atan et al. [32] investigated red mud and agricultural residues for lightweight, durable ceramic bricks. Karslıoğlu et al. [33] further improved thermal and sound insulation by incorporating recycled rubber and plastics into brick production. Beyond bricks, Ulugol et al. [34] developed self-healing geopolymer composites with superior durability using gypsum, glass, and wood waste. Meanwhile, Erdogmus et al. [35] optimized the recycling of marble cutting waste for enhanced durability, and Uysal et al. [36] demonstrated the potential of geopolymer composites using waste marble, brick, and ceramic powders.

Collectively, these studies, summarized in **Table 3**, reflect Turkey's progressive journey in CDW recycling. From pioneering efforts in brick production to advanced composites and disaster recovery, the integration of recycled materials into construction practices highlights innovations that enhance sustainability, material performance, and cost-effectiveness. These efforts not only address pressing environmental challenges but also position Turkey as a leader in circular construction and sustainable urban development.

4. Methodology and proposed applications of recycled waste materials in engineering projects in Turkey

The preceding review highlights significant progress in the recycling of Construction and Demolition Waste (CDW) in Turkey, emphasizing its potential for sustainable construction. However, several critical gaps remain, including the limited adaptation of recycled materials to local climatic conditions, such as freeze-thaw cycles and seismic activity, and the absence of standardized frameworks for large-scale implementation. To address the critical gaps identified in the use of recycled CDW, particularly in challenging conditions like freeze-thaw cycles and seismic activity, a standardized, end-to-end framework is proposed (**Figure 1**).

4.1 Step 1: Material collection and source-separation

Effective management of CDW in Turkey begins with material collection and source separation. Centralized recycling hubs near urban transformation zones and infrastructure projects are crucial for efficiently processing CDW into high-quality fractions such as RCA and RAP. These hubs minimize transportation costs, reduce environmental impact, and ensure a steady supply of recycled materials. Key processes, technologies, and outcomes are summarized in **Table 4**.

Advanced technologies such as optical sorters and magnetic separators streamline the recycling process by improving material purity and reducing manual sorting. On-site segregation of concrete, asphalt, metals, and plastics is equally critical, minimizing contamination and facilitating downstream processing. Digital tools, such as QR code-based bin tracking systems, enhance compliance and logistics. To maintain the quality of recycled materials, facilities must adhere to strict impurity thresholds (e.g., <5% contamination for RCA and RAP) and employ rigorous quality assurance protocols, including advanced testing and digital monitoring. Training and

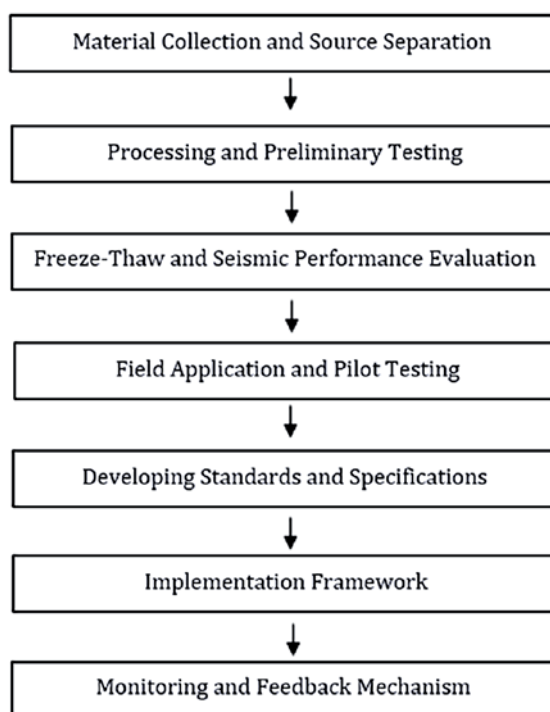


Figure 1.
Recycling process flowchart.

capacity-building initiatives for contractors and site managers ensure widespread compliance and foster a culture of sustainability.

This approach offers significant benefits, including a 50–60% CDW recovery rate, reducing landfill dependency, and yielding 10–12 million tons of RCA and RAP annually. These measures also lower construction costs by 15–20% and create jobs, supporting Turkey’s transition to sustainable urban development and circular construction practices.

4.2 Step 2: Processing and preliminary testing

The processing and testing of RCA and RAP are vital to ensure their suitability for engineering applications. **Table 5** summarizes the critical properties, testing methods, and engineering applications of these materials.

Preliminary testing assesses physical, chemical, and mechanical properties, with standardized methods like sieve analysis (ASTM C136) and abrasion resistance (ASTM C131) ensuring compliance with engineering standards. Specialized tests, such as freeze-thaw durability (ASTM C666), confirm resilience under extreme conditions. Quality assurance protocols, including batch testing and compliance certificates, guarantee material consistency and traceability.

Capacity-building efforts, such as workshops and knowledge-sharing platforms, are essential for training facility operators and engineers in advanced processing and testing techniques. These initiatives improve material handling and bolster stakeholder confidence. Adopting these strategies offers significant environmental

Process	Key actions	Technologies used	Expected outcomes	Challenges addressed
Material collection	Establish centralized recycling hubs near urban transformation and high-waste generation areas.	Optical sorters, magnetic separators, screening systems	Steady supply of RCA and RAP, reduced transportation costs, minimized environmental impact	Inefficient waste logistics, high transportation costs
	Collaborate with municipalities and private sector for funding and operation of hubs.			Limited recycling infrastructure
Source separation	Implement mandatory on-site segregation of concrete, asphalt, metals, wood, and plastics.	QR code tracking systems, labeled bins	Higher material purity, streamlined downstream recycling processes	Contamination of recyclable materials
	Provide training for contractors and workers on sorting techniques and benefits of recycling.		Increased compliance, awareness of recycling practices	Low awareness and lack of sorting expertise
Quality assurance	Establish impurity thresholds for recycled materials (e.g., <5% contamination for RCA and RAP).	X-ray fluorescence, chemical analysis tools	Consistent material quality, acceptance in engineering applications	Low-quality recycled materials
	Conduct regular inspections and digital monitoring of recycling facilities.	Digital monitoring platforms	Transparent tracking of recovery rates, contamination levels	Lack of accountability and data integration
Environmental and economic impact	Recover 50–60% of CDW, reducing landfill dependency and environmental degradation.		Recovery of 10–12 million tons of RCA/RAP annually, 15–20% cost savings in construction	Over-reliance on natural aggregates
	Create job opportunities in recycling and green construction sectors.		Economic activity stimulation, sustainable urban development	Limited economic incentives for recycled materials

Table 4.
Key processes and outcomes in effective collection and separation of CDW.

and economic benefits, including reduced landfill dependency, resource conservation, and cost savings. By implementing rigorous processing and testing frameworks, municipalities and industries can advance the integration of recycled materials into sustainable infrastructure development.

4.3 Step 3: Freeze-thaw and seismic performance evaluation

Evaluating the freeze-thaw durability and seismic resistance of RCA and RAP is crucial for infrastructure projects in regions with harsh climatic and seismic conditions. Laboratory tests like freeze-thaw durability (ASTM C666) and cyclic triaxial compression (ASTM D5311) simulate environmental stresses to assess material

Property	Test method	Purpose	Required range	Applications
Particle size distribution	Sieve analysis (ASTM C136, EN 933-1)	Ensure grading suitability for road base, sub-base, or asphalt layers	Compliant with project-specific grading limits	Road bases, sub-bases, asphalt layers
Wear resistance (Abrasion)	Los Angeles Abrasion Test (ASTM C131, EN 1097-2)	Assess resistance to wear under mechanical loading	< 40% material loss	High-stress applications, pavement layers
Impact resistance (Toughness)	Aggregate Impact Value Test (BS 812-112)	Determine toughness for dynamic loading applications	< 25% material loss	Dynamic loading scenarios, road construction
Water absorption	Water Absorption Test (ASTM C127, EN 1097-6)	Evaluate porosity and performance under wet conditions	< 3% for high-quality aggregates	Wet environments, freeze-thaw regions
Specific gravity	Specific Gravity Test (ASTM C128, EN 1097-6)	Establish material density for load-bearing applications	2.5-2.8 for most applications	Structural applications requiring load-bearing capacity
Freeze-thaw durability	Freeze-Thaw Test (ASTM C666)	Assess material durability under freeze-thaw conditions	> 90% strength retention after 10 cycles	Cold regions or areas with repeated freeze-thaw cycles
Compressive strength	Compressive Strength Test (ASTM C39)	Determine load-bearing capacity under compressive stress	> 20 MPa for RCA-based concrete	Structural concrete, foundations, pavement layers
Flexural strength	Flexural Strength Test (ASTM C78, EN 12390-5)	Evaluate resistance to bending under flexural stress	> 3.5 MPa for flexural strength in pavements	Bridges, pavements, load-bearing structures
Modulus of elasticity	Modulus of Elasticity Test (ASTM C469)	Assess elasticity and deformation under load	Compliant with design specifications (> 20 GPa typical)	Buildings, bridges, flexible pavements
Thermal conductivity	Thermal Conductivity Test (ASTM C177)	Measure thermal performance for temperature-sensitive applications	< 1.5 W/mÂ·K for insulation applications	Insulation layers, cold regions, thermal management
Chemical reactivity (sulfates, chlorides)	Chemical Analysis for Sulfates and Chlorides (ASTM C1152)	Identify harmful chemical interactions that affect durability	Within safe thresholds (e.g., < 0.1% sulfate, < 0.05% chloride)	Coastal structures, durability-focused applications
Permeability	Permeability Test (ASTM D5084)	Evaluate drainage properties for hydraulic applications	< 10 ⁻⁵ cm/s for low-permeability layers	Drainage systems, hydraulic applications
Resilient modulus	Resilient Modulus Test (AASHTO T307)	Measure stiffness under repeated loading	> 200 MPa for base and subbase layers	Pavement bases and subbases under heavy traffic
Fatigue resistance	Fatigue Resistance Test (ASTM D7460)	Assess long-term performance under cyclic loading	> 10 ⁵ cycles before failure	Flexible pavements, high-traffic roads
Alkali-silica reactivity	Alkali-Silica Reactivity Test (ASTM C1260, ASTM C1567)	Identify potential for harmful expansions due to ASR	Non-reactive or within safe limits	Concrete durability, long-term stability

Property	Test method	Purpose	Required range	Applications
Sulfate soundness	ASTM C88	Evaluate resistance to weathering and chemical exposure	Compliant with ASTM or local project limits	Coastal regions, salt-exposed structures
Long-term aging	AASHTO R30	Simulate aging under environmental conditions	No excessive degradation over test cycles	Pavements and structures under aging conditions
Leachate analysis	EPA Method 1311	Detect harmful leachates	Below regulatory safety thresholds	Sensitive areas like water reservoirs
Heavy metal contamination	ISO 17294-2	Quantify heavy metal content	Below regulatory thresholds for residential use	Residential and public infrastructure
Triaxial compression	ASTM D7181	Assess shear strength under triaxial loading	Compliant with project design criteria	Subbases, embankments, retaining walls
Dynamic modulus	AASHTO T342	Measure stiffness under dynamic loading	Compliant with stiffness requirements for pavements	High-traffic roads, pavements
Drainage capacity	EN 12697-40	Evaluate water flow through aggregates	Sufficient flow capacity for drainage	Permeable pavements, drainage systems
Capillary rise	ASTM C1585	Assess moisture movement in aggregates	Minimal capillary rise for freeze-thaw regions	Freeze-thaw environments, wet conditions
Coefficient of thermal expansion (CTE)	AASHTO T336	Determine expansion behavior under temperature changes	Within safe expansion limits for design	Extreme temperature zones
Acoustic absorption	ISO 354	Evaluate sound absorption properties	High absorption for noise-reducing applications	Urban and highway noise reduction
Microstructure analysis (SEM)	SEM Analysis	Examine microstructure of recycled aggregates	Clear and uniform microstructure for quality	Advanced material research and quality
Crystalline phase analysis (XRD)	X-Ray Diffraction (XRD)	Analyze crystalline phases for durability	Non-reactive or within safe limits	Long-term durability applications
Adhesion between RAP and binder	EN 12697-12	Measure binder adhesion to RAP	Strong binder adhesion ensuring durability	High-stress pavement and asphalt layers

Table 5.
Critical properties, testing methods, and engineering applications of RCA and RAP.

performance. Key metrics include strength retention (>90% after 10 cycles) and weight loss (<3%), which ensure suitability for cold climates and seismic-prone areas. Freeze-thaw tests verify resilience, while triaxial tests determine properties like stiffness modulus (>200 MPa) and shear strength (>200 kPa) for structural applications. Numerical modeling complements testing by predicting long-term performance, aiding in material optimization. By adhering to benchmarks summarized in **Table 6**,

Property	Test method	Purpose	Required value	Applications
Freeze-thaw durability	Freeze-Thaw Test (ASTM C666)	Evaluate durability under repeated freeze-thaw cycles	> 90% strength retention after 10 cycles	Cold regions, pavement bases, structural layers
Strength retention	Compressive Strength Test (ASTM C39)	Assess strength retention after exposure to freeze-thaw cycles	> 20 MPa for structural applications	Road bases, structural concrete, pavements
Weight loss	Freeze-Thaw Weight Loss Measurement (ASTM C666)	Measure material degradation during freeze-thaw cycles	< 3% weight loss after 10 cycles	Pavement layers, embankments, freeze-thaw regions
Shear strength	Triaxial Compression Test (ASTM D7181)	Determine shear strength under triaxial loading	> 200 kPa for subbase and embankments	Subbases, embankments, retaining walls
Stiffness modulus	Cyclic Triaxial Test (ASTM D5311)	Assess stiffness under cyclic loading conditions	> 200 MPa for pavement layers	Flexible pavements, high-stress road layers
Permanent deformation	Cyclic Triaxial Test (ASTM D5311)	Evaluate deformation after repeated seismic loading	< 5% permanent deformation	Seismic zones, critical infrastructure
Seismic load resistance	Dynamic Modulus Test (AASHTO T342)	Assess resistance to dynamic seismic forces	Compliant with design seismic stress levels	Seismic-prone regions, road bases
Dynamic elastic modulus	Dynamic Modulus Test (AASHTO T342)	Measure material elasticity under dynamic conditions	> 20 GPa for most structural uses	Dynamic loading scenarios, bridges
Residual strength	Residual Strength Test (ASTM C469)	Determine residual strength post-seismic events	> 80% of initial strength	Post-seismic reconstruction, critical applications

Table 6.
Key properties, testing methods, and performance standards for freeze-thaw and seismic applications of RCA and RAP.

RCA and RAP demonstrate their potential to withstand extreme conditions, ensuring their reliability in sustainable infrastructure projects.

Numerical modeling extends the insights gained from laboratory tests to predict long-term behavior under real-world conditions. Advanced finite element modeling tools, such as PLAXIS and ABAQUS, simulate RCA and RAP behavior in applications like road bases, embankments, or pavement layers. These models incorporate parameters such as stiffness modulus, dynamic elastic modulus, and material composition to forecast outcomes like settlement, fatigue, and cracking under freeze-thaw or seismic stresses. For example, parametric analyses performed in these simulations highlight the effects of aggregate size, moisture content, and binder type on performance. Such findings enable the optimization of material design, ensuring structural integrity under high-stress conditions.

To translate laboratory and modeling results into practical guidelines, materials selected for freeze-thaw or seismic zones must adhere to the established benchmarks. For example, RCA and RAP intended for cold regions should demonstrate >90% strength retention after freeze-thaw cycles and minimal deformation under seismic forces. Design enhancements, such as improved compaction techniques or safety factors for critical structures, can mitigate risks. Field monitoring systems equipped with strain gauges, accelerometers, and temperature sensors are crucial for real-time performance assessments.

The integration of these findings into region-specific standards and construction codes ensures the confidence of stakeholders in adopting recycled materials. Moreover, the incorporation of numerical modeling results into design practices facilitates the application of RCA and RAP in highly demanding environments.

By combining rigorous laboratory testing, advanced numerical modeling, and practical implementation strategies, this evaluation framework ensures that RCA and RAP meet the structural and durability requirements for use in regions prone to freeze-thaw cycles and seismic activity. This comprehensive approach enhances the resilience and sustainability of infrastructure, positioning recycled materials as viable, eco-friendly solutions for modern engineering challenges.

To support the performance evaluation discussed above and ensure alignment with national standards, a detailed methodological approach was developed to guide laboratory testing and application-specific assessments under Turkey's climatic and structural conditions. To evaluate the engineering viability of Recycled Concrete Aggregate (RCA) and Reclaimed Asphalt Pavement (RAP) under Turkey's diverse climatic and geotechnical conditions, a comprehensive methodological framework was developed. This approach integrates detailed laboratory characterization of material properties with performance-based testing tailored for application-specific requirements. All procedures were aligned with relevant Turkish specifications and internationally recognized standards to ensure consistency and practical relevance. Key engineering parameters—including Proctor compaction characteristics, California Bearing Ratio (CBR), resilient modulus, compressive strength of RCA-based concrete, asphalt mixture stiffness, and durability under cyclic environmental and mechanical stresses (e.g., freeze-thaw and repeated loading)—were evaluated using the standardized protocols. These included ASTM D698 for compaction, AASHTO T193 for CBR, ASTM D7382 for resilient modulus, ASTM C39/TS EN 12390-3 for compressive strength, EN 12697-22 for wheel tracking of asphalt mixtures, and ASTM C666 for freeze-thaw resistance of concrete materials. The results of these tests were benchmarked against specification criteria outlined by the Turkish General Directorate of Highways (KGM) and national standards (TS), enabling the identification of threshold values and performance margins for various engineering applications. This methodology not only ensures regulatory compliance but also facilitates performance optimization through context-specific material selection and mix design strategies. The proposed applications for RCA and RAP are presented in the following sections, accompanied by tailored enhancement methods designed to address the demands of distinct climatic zones and structural performance requirements across Turkey.

4.4 Step 4: Field application and pilot testing

Field validation of RCA and RAP ensures their performance under real-world conditions, bridging the gap between laboratory findings and practical applications. Pilot projects, strategically located in diverse climatic and seismic regions, assess

metrics such as settlement, rutting, and cracking under traffic loads and freeze-thaw stresses (see **Table 7** for details). Instruments like strain gauges, accelerometers, and temperature sensors monitor material behavior, providing critical data for optimizing design practices.

Collected data are analyzed to refine material specifications, confirm durability benchmarks, and evaluate cost-effectiveness. Case studies, such as pilot roads in freeze-thaw zones, inform best practices for handling, compaction, and pre-treatment, enabling scalable implementation.

The findings guide the creation of comprehensive guidelines tailored for regional conditions, fostering stakeholder confidence in RCA and RAP. By confirming material durability and reducing reliance on virgin aggregates, pilot projects advance sustainable construction practices, positioning Turkey as a leader in eco-friendly infrastructure development.

To demonstrate the applicability of RCA under practical field conditions, a representative pilot case involving urban highway base construction in Turkey is presented. This application scenario operationalizes the previously established methodological framework and performance criteria, utilizing RCA derived from demolition waste

Category	Details
Objective	Validate laboratory findings and assess real-world performance of RCA and RAP under field conditions.
Key actions	• Construct pilot projects in diverse regions (freeze-thaw zones, seismic-prone areas). • Implement standard construction practices (e.g., optimized compaction and moisture control).
Metrics evaluated	• Settlement (vertical displacement in embankments and subbases). • Rutting (deformation in flexible pavements under traffic loads). • Cracking (occurrence and propagation in pavements). • Strength retention and durability (under freeze-thaw and seismic stresses).
Instrumentation used	• Strain gauges: Measure strain levels under dynamic and static loads. • Accelerometers: Record vibrations and accelerations during seismic events. • Temperature sensors: Monitor freeze-thaw effects. • Displacement transducers: Measure surface and subsurface movements.
Data collection and analysis	• Real-time monitoring systems to transmit data to centralized databases. • Analyze trends to refine material specifications and validate laboratory predictions. • Conduct cost-benefit analyses to highlight economic advantages.
Expected outcomes	• Confidence in RCA and RAP performance for large-scale adoption. • Comprehensive guidelines for implementation, including material specifications and monitoring protocols. • Reduction in costs and environmental impacts compared to traditional materials.
Challenges addressed	• Discrepancies between laboratory and real-world performance. • Durability in extreme conditions (freeze-thaw, seismic stresses). • Ensuring consistent material quality across applications.

Table 7.
Objectives, methods, and outcomes of field validation for RCA and RAP.

collected in the Istanbul metropolitan area. One of the most promising engineering applications of RCA in Turkey is its use as a granular base or subbase material in road infrastructure, particularly for urban highways subjected to heavy traffic loading. To ensure the structural integrity and long-term performance of RCA in base layers, the material must comply with the established grading and cleanliness specifications. In this context, our methodological approach involves controlled blending and gradation refinement of RCA to meet the requirements outlined in the Turkish Highway Technical Specifications (KTS) for base coarse aggregates. Typically, this process includes the crushing and sieving of demolition concrete to produce a well-graded aggregate mix—commonly within the 0–38-mm size range—falling within the prescribed upper and lower bounds of particle size distribution. Appropriate gradation not only enhances compaction characteristics, resulting in maximized dry density, but also improves load distribution and reduces internal voids. In field trials using RCA sourced from Istanbul's demolition waste, the as-received material initially failed to meet gradation and plasticity criteria. However, after appropriate reprocessing, the RCA complied fully with KTS particle size and plasticity limits and exhibited satisfactory geotechnical properties for pavement base applications. Compaction and moisture conditioning are also critical to achieving adequate field performance. Using the Modified Proctor method, we determined the optimum moisture content for RCA, which tends to be slightly higher than that of natural aggregates due to the presence of porous residual mortar. Field compaction exceeding 95% of the maximum dry density is recommended to ensure that the *in situ* stiffness modulus surpasses 200 MPa—indicative of a structurally competent base layer capable of sustaining repeated axle loads from heavy vehicles. Laboratory evaluations, including plate loading and resilient modulus testing of compacted RCA base specimens, yielded modulus values in the range of 120–160 MPa under moderate confining stress. Extrapolation to field conditions that involve higher confinement beneath pavement layers suggests achievable stiffness values exceeding 200 MPa. These performance metrics are comparable to those of conventional crushed stone bases, thereby confirming that well-processed RCA can serve as a viable alternative in urban highway base construction without compromising structural performance or deformation resistance.

Beyond fundamental mechanical suitability, additional measures can be employed to further enhance the long-term performance of RCA in heavily trafficked base layers. Moreover, expanding the scope of RCA utilization beyond unbound layers offers further opportunities for sustainability and material circularity in Turkish infrastructure projects. To further enhance RCA's performance under high traffic loadings, the permanent deformation (rutting) behavior of RCA base layers was investigated through repeated load triaxial (RLT) testing and large-scale cyclic plate loading. Results demonstrated that blended base materials containing 50% RCA and 50% virgin aggregate exhibited permanent strain accumulation comparable to that of 100% natural aggregate bases, even after 10,000 load repetitions. Although fully recycled RCA bases displayed slightly higher cumulative deformation, the strain levels remained within acceptable serviceability limits. In high-stress areas such as toll plazas, logistics centers, or industrial zones, performance can be significantly improved through light stabilization techniques. Laboratory testing revealed that the incorporation of 2–3% Portland cement into the RCA base mix effectively reduced permanent deformation. This is attributed to the interaction between the residual mortar fines and newly formed cementitious bonds, resulting in enhanced cohesion. Notably, cyclic plate load testing of 100% RCA base layers stabilized with 3% cement yielded elastic deformation and strain response equivalent to that of natural aggregate

controls. This approach aligns with the design principles of hydraulically bound materials as per EN 14227, and it offers added benefits in seismic zones, where increased cohesion helps mitigate differential settlement under ground shaking.

Following the successful implementation of RCA in road base applications, its potential use as a coarse aggregate in concrete mixtures has also been explored. When properly processed and integrated through tailored mix design strategies, RCA can replace a portion of natural aggregates in structural and non-structural concrete without compromising key mechanical and durability requirements. The next section presents the methodological framework and experimental outcomes for RCA-based concretes, with particular attention to performance under Turkey's diverse climatic conditions. For structural concrete applications, an RCA replacement level of approximately 30% by mass was identified as the optimal threshold, while replacement ratios up to 50% were deemed acceptable for conventional concrete mixes. Within these bounds, trial mixtures achieved compressive strengths in the range of 25–30 MPa, confirming their suitability for a variety of infrastructure components.

Several integrated design measures were adopted to ensure consistent performance and long-term durability. Firstly, all RCA was conditioned to a Saturated Surface Dry (SSD) state prior to batching, minimizing uncontrolled water absorption during mixing and thereby improving workability and strength predictability. Secondly, the binder system was adjusted through an increase in cement content (approximately 10%) and the incorporation of supplementary cementitious materials such as fly ash and silica fume. These additions served to refine the pore structure of the concrete matrix and enhance bonding within the interfacial transition zone (ITZ), a critical factor in recycled aggregate concrete (RAC).

In regions subject to severe freeze-thaw cycles, such as Eastern Turkey, air-entraining admixtures were incorporated to introduce a controlled air-void system of 4–6%, in accordance with ASTM C260. Laboratory durability testing confirmed that RAC samples retained over 90% of their dynamic modulus after 300 freeze-thaw cycles, a result nearly equivalent to that of conventional concrete. All mixes were designed in compliance with TS 802 (Turkish standard for concrete mix design), and mechanical and durability testing was conducted in accordance with TS EN 12390-3 for compressive strength and TS EN 12390-9 for freeze-thaw performance. These tests consistently demonstrated that RCA-based concretes met or exceeded the minimum requirements for both strength (≥ 20 MPa) and freeze-thaw resistance ($\geq 90\%$ retention).

Overall, RCA can be effectively utilized in concrete for a wide range of urban infrastructure applications, including sidewalks, medians, and low-rise structural components. Even in load-bearing elements and pavement slabs exposed to mechanical and climatic stresses, partial incorporation of RCA did not compromise performance. Notably, previous studies have shown that RAC members also maintain comparable seismic performance metrics—such as ductility and energy dissipation capacity—relative to natural aggregate concrete, supporting their use in seismically active regions. Thus, through appropriate mix design and quality control, the integration of RCA in concrete contributes meaningfully to sustainable construction practices while maintaining full compliance with Turkish performance standards.

In parallel with the practical applications of RCA, Reclaimed Asphalt Pavement (RAP) also presents considerable potential for integration into both bound and unbound layers of road infrastructure. Given Turkey's evolving regulatory landscape and increasing emphasis on sustainable highway design, RAP-based solutions—when aligned with performance-oriented mix designs and stabilization techniques—can

offer both environmental and engineering benefits. The following section details the methodological approach and pilot-scale evaluations of RAP incorporation into asphalt surface mixtures and base layers, reflecting regional traffic demands and climatic variations.

In surface course applications, RAP can be successfully incorporated into hot-mix and warm-mix asphalt mixtures at moderate-to high-replacement levels, typically ranging from 15 to 50%. However, due to the aged and stiff nature of the residual bituminous binder in RAP, binder selection must be carefully adjusted. To maintain target performance levels, the use of softer virgin binders—one penetration grade lower than standard—is recommended, ensuring that the composite binder exhibits sufficient flexibility. For example, if a PG 64-22 binder is typically specified, its substitution with a PG 58-28 binder when incorporating 50% RAP has been shown to preserve ductility and fatigue life, consistent with ASTM D4887 and AASHTO M323 recommendations. As a complementary measure, rejuvenating additives such as bio-based oils or aromatic extracts can be employed to restore maltene content and improve low-temperature cracking resistance. Fatigue testing using four-point bending beam protocols (EN 12697-24) revealed that rejuvenated mixes with 50% RAP content exhibited fatigue lives within 90% of conventional (RAP-free) mixes, demonstrating that high RAP mixtures can meet structural performance criteria with proper modification. Mix homogeneity and plant-level integration also play a critical role. RAP is fractionated into coarse and fine components to improve blend control, and mixing processes are calibrated to ensure full coating of aggregates. Superpave gyratory compaction and the Marshall method (per TS EN 13108) are used to design for air void targets around 4%, while verifying voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) remains within specification. Slight increases in plant mixing temperatures or extended mixing times may be applied to offset the stiffening effect of aged binder. To confirm rutting resistance, Hamburg Wheel Tracking Tests (EN 12697-22) were conducted. In these tests, a 50% RAP mix exhibited a rut depth of only 4 mm after 10,000 load cycles at 50°C, outperforming the control mix (7 mm rut depth). These results are particularly relevant for high-temperature zones such as Southeastern Turkey. Moisture susceptibility was also evaluated using Modified Lottman tests (AASHTO T283), with tensile strength ratios exceeding 80% when anti-stripping agents were used—complying with TS 11515 specifications for water damage resistance. Collectively, these findings confirm that with suitable binder strategies and performance testing, RAP can be reliably employed in asphalt layers across Turkey's climate zones.

In addition to bound layers, RAP may be utilized in granular base or sub-base layers, either unbound, blended with natural aggregates, or stabilized with hydraulic or chemical additives. While pure RAP aggregate often shows reduced shear strength and soaked California Bearing Ratio (CBR) values below the 100–120 threshold required by KGM for base layers, blending RAP with virgin aggregates significantly improves performance. Laboratory results demonstrated that a 20% RAP blend with 80% crushed stone achieved soaked CBR values above 130, indicating its suitability for base course construction without further treatment. This configuration also improved compaction and did not exhibit degradation under freeze-thaw cycles. For higher RAP utilization in base layers, stabilization with Portland cement or alternative binders is recommended. Tests incorporating 3% pozzolanic cement by weight into 100% RAP samples resulted in soaked CBR values exceeding 150, alongside resilient modulus values greater than 500 MPa. These cement-treated RAP layers exhibited negligible permanent deformation under cyclic plate loading, supporting their use

in heavily trafficked urban settings or seismic regions. The dual binding action of asphalt and cement creates a cohesive and durable material, functionally equivalent to hydraulically bound layers as defined in EN 14227. Additional stabilization strategies—such as the inclusion of Class C fly ash (10–15%)—have also proven effective. Fly ash sourced from Turkish thermal power plants was mixed with RAP to enhance stiffness and early-age strength. After 7 days of curing, fly ash-treated RAP demonstrated a 40% increase in resilient modulus, providing an economical solution for secondary roads or temporary pavements. Moreover, cold in-place recycling (CIPR) techniques using foamed bitumen or asphalt emulsions have shown promise in field applications. These methods enable the on-site reuse of existing asphalt layers, combined with RAP, to produce cold-recycled base materials with adequate mechanical performance—consistent with recent KGM circulars on cold recycling practices. Field implementation of RAP base layers should also consider drainage and thermal performance. Although RAP is inherently hydrophobic, void spaces can still retain moisture. Therefore, placement over a well-draining subbase and provision of lateral drainage is essential. Laboratory tests measuring hydraulic conductivity ($\sim 10^{-3}$ to 10^{-4} cm/s) indicated that RAP functions effectively as a free-draining layer, minimizing frost heave potential. Its flexibility relative to crushed stone also allows for better energy dissipation during seismic events, reducing the risk of reflective cracking in overlying asphalt layers. In summary, the proposed methodology demonstrates that RAP can be successfully utilized in both asphalt mixtures and pavement foundation layers, provided that regional design standards and environmental conditions are accounted for. Through a combination of material characterization, binder optimization, and stabilization techniques, RAP can meet the mechanical, thermal, and durability requirements of Turkish road infrastructure while significantly reducing reliance on virgin materials.

4.5 Step 5: Developing standards and specifications

Establishing clear standards and specifications is essential for ensuring the reliable use of RCA and RAP in Turkey's infrastructure projects. These standards address material performance thresholds, testing protocols, and implementation strategies tailored to the country's diverse environmental conditions. Key benchmarks, such as freeze-thaw durability (>90% strength retention after 10 cycles) and seismic resistance (shear strength >200 kPa), guide material suitability for specific applications. **Table 8** outlines the critical components of this framework.

Regional challenges, such as freeze-thaw conditions in eastern Turkey or chloride exposure in coastal areas, necessitate targeted performance thresholds. Standards like ASTM C666 and TS EN 933-1 ensure consistent material quality. Advanced design tools, including numerical modeling with PLAXIS or FLAC, support the integration of recycled materials into seismic-prone regions. Practical implementation strategies, including field validation through pilot projects and training programs, are critical for compliance and widespread adoption. Monitoring and feedback loops ensure continuous improvement by refining standards based on real-world data. This iterative approach enhances stakeholder confidence and aligns recycled material use with sustainability goals.

The establishment of well-defined standards offers several advantages. Uniform material quality and performance across projects build reliability and confidence among stakeholders. Additionally, the widespread adoption of recycled materials supports sustainability goals by reducing landfill dependency, conserving natural

Aspect	Details	Examples/Benchmarks	Impact on construction
Material performance thresholds	Establish region-specific durability and strength benchmarks based on environmental challenges.	- Freeze-thaw regions: >90% strength retention after 10 cycles, <3% weight loss (ASTM C666). - Seismic zones: Shear strength >200 kPa, stiffness modulus >200 MPa.	Ensures RCA/RAP perform reliably under varying climatic and seismic conditions.
Testing standards	Standardized testing protocols to evaluate material suitability for specific conditions.	- Freeze-thaw durability: ASTM C666. - Chemical durability (chlorides/sulfates): ASTM C1152, ASTM C88. - Stiffness Modulus: AASHTO T342.	Establishes credibility and comparability of materials for construction applications.
Integration into design codes	Incorporate RCA/RAP specifications into national construction codes.	- TS EN 933-1: Particle size distribution. - TS EN 13242: Specifications for unbound aggregates. - Use PLAXIS/FLAC for seismic analysis.	Encourages acceptance of RCA/RAP in public/private projects; supports policy alignment and scalability.
Implementation guidelines	Provide practical steps for adopting RCA/RAP in field applications.	- Field validation: Pilot projects to simulate real-world conditions. - Training programs for engineers and contractors. - Pre-treatment for freeze-thaw resistance.	Builds confidence in materials; improves performance through informed application strategies.
Monitoring and feedback	Create iterative processes for refining standards and improving material performance.	- Feedback loops from pilot projects. - Monitoring systems to track field performance. - Regular updates to performance thresholds and testing standards.	Enhances long-term reliability and sustainability of RCA/RAP in construction practices.
Benefits of standardization	Uniformity, sustainability, and cost-efficiency in construction practices.	- Reduced landfill dependency. - Lower project costs (15–20%). - Consistent material quality and performance.	Supports circular economy goals; minimizes environmental footprint while maximizing economic and structural benefits

Table 8.
Framework for standardizing the use of RCA and RAP.

resources, and lowering greenhouse gas emissions. Clear guidelines also help optimize material usage, lowering project costs and supporting economic efficiency.

By tailoring standards and specifications to Turkey’s unique environmental and infrastructural challenges, this approach facilitates the integration of RCA and RAP into mainstream construction practices. Collaboration among engineers,

policymakers, and industry stakeholders is essential to realize the full potential of recycled materials, transforming them into reliable and sustainable components of Turkey's construction landscape.

4.6 Step 6: Implementation framework

The adoption of RCA and RAP in Turkey's construction projects requires a structured framework addressing knowledge gaps, economic incentives, and

Components	Key actions	Expected outcomes	Stakeholders involved
Training Programs	Conduct workshops on material handling, standardized testing (e.g., ASTM C666, ASTM C136), and application techniques.	Enhanced technical capacity among engineers, contractors, and municipal staff.	Municipalities, engineers, contractors
	Develop online platforms for knowledge sharing, troubleshooting, and discussing innovative applications.	Increased knowledge dissemination and collaborative problem solving.	Industry associations, policymakers
Economic incentives	Offer subsidies for certified recycled materials to reduce initial costs.	Increased adoption of RCA and RAP due to improved affordability.	Municipalities, developers, private sector
	Provide tax reductions or credits for projects meeting recycled content thresholds.	Greater participation from private sector projects.	Government, developers
	Link recycled material use to green certifications (e.g., LEED, BREEAM).	Accelerated permitting processes and recognition for sustainable construction practices.	Certifying bodies, developers
Policy support	Mandate recycled material use in public procurement for infrastructure projects.	Guaranteed market demand for RCA and RAP, fostering consistent adoption.	Municipalities, public infrastructure bodies
Lifecycle assessment tools	Utilize LCA tools (e.g., SimaPro, GaBi) to model environmental and economic benefits.	Quantifiable data on carbon reduction, resource conservation, and cost savings.	Municipalities, developers, environmental agencies
	Conduct scenario analyses to compare material sourcing strategies.	Identification of the most sustainable and cost-effective approaches.	Engineers, policymakers
Long-term benefits	Incorporate LCA findings into public reports and sustainability plans.	Improved public transparency and stakeholder trust in recycled material initiatives.	Municipalities, government bodies
	Stimulate economic growth through increased activity in recycling and green construction sectors.	Job creation and expanded market for sustainable construction materials.	Recycling industry, private developers

Table 9.
Implementation framework for RCA and RAP adoption in sustainable construction.

environmental benefits. This involves training programs, supportive policies, and lifecycle assessment (LCA) tools to ensure widespread and consistent use of recycled materials, as summarized in **Table 9**.

Training Programs focus on material handling, testing methods (e.g., ASTM C136, ASTM C666), and application techniques, equipping stakeholders with the skills to use RCA and RAP effectively. Workshops and knowledge-sharing platforms foster collaboration and innovation across the sector. Economic Incentives, such as subsidies and tax reductions for recycled materials, encourage adoption in private sector projects. Linking recycled material use to green certifications like LEED and BREEAM provides additional motivation by streamlining permitting and enhancing recognition for sustainable practices. Policy support, including mandatory recycled material use in public procurement, ensures steady demand and promotes industry-wide compliance with sustainability goals. Lifecycle assessment tools like SimaPro and GaBi enable data-driven decisions by quantifying environmental and economic benefits, supporting transparency and stakeholder trust.

Implementing this framework offers extensive benefits for Turkey's construction sector. Training programs and economic incentives lower barriers to adoption, enhancing the use of RCA and RAP. Environmental sustainability is bolstered through the quantifiable reduction of carbon footprints and resource conservation, aligning construction practices with global climate goals. Economic growth is stimulated through increased activity in recycling and green construction sectors, while regulatory compliance ensures infrastructure projects meet modern performance standards. By fostering collaboration among stakeholders and emphasizing measurable outcomes, this strategy advances the country's transition toward a circular economy and sustainable urban development.

4.7 Step 7: Monitoring and feedback mechanism

Monitoring and feedback mechanisms are vital for ensuring the long-term performance and compliance of RCA and RAP in construction projects. These mechanisms involve collecting real-world data, refining standards, and fostering collaboration among stakeholders. **Table 10** summarizes the core components, tools, expected outcomes, and challenges addressed in the monitoring framework.

Feedback loops play a critical role in converting real-world data into actionable improvements. Metrics, such as strength retention and rutting resistance, gathered from pilot projects and lifecycle assessments (LCA), guide refinements to material standards and testing protocols. This iterative process aligns standards with actual performance and ensures that RCA and RAP applications remain effective and reliable across varying conditions. For instance, comparing field performance to laboratory benchmarks highlights any discrepancies and drives updates to technical guidelines.

Centralized digital platforms streamline the sharing and analysis of performance data. These systems enable municipalities and stakeholders to track metrics such as compressive strength and stiffness modulus in real time, ensuring consistency and transparency. Incident reporting systems and repositories of best practices further enhance knowledge dissemination and support the replication of successful applications. These platforms also enable automated alerts for non-compliance, ensuring prompt corrective actions.

Advanced monitoring technologies, including strain gauges, accelerometers, and temperature sensors, provide high-accuracy data on material performance under

Component	Action/ description	Tools/ technologies	Expected outcome	Challenges addressed
Feedback loops	Collect real-world performance data to refine standards and protocols.	Pilot project metrics, LCA results, regular stakeholder feedback	Improved material standards and protocols tailored to real-world conditions.	Discrepancies between lab predictions and field performance.
Digital reporting platforms	Centralized systems for real-time data sharing and knowledge dissemination.	Cloud-based databases, incident reporting modules, knowledge repositories	Transparent performance monitoring, efficient issue resolution, and enhanced collaboration.	Inefficient data management and lack of knowledge sharing.
Advanced monitoring technologies	Deploy systems to measure real-time material behavior under environmental and mechanical stresses.	Sensor networks (strain gauges, accelerometers, temperature sensors), IoT integration, remote monitoring tools	High accuracy in performance data collection and proactive problem identification.	Delays in identifying issues and inaccuracies in field data.
Expected outcomes	Continuous improvement in standards, enhanced material reliability, and sustainability advancements.	Collaboration among municipalities, contractors, and engineers.	Increased stakeholder confidence and broad adoption of RCA and RAP in sustainable construction practices.	Resistance to adoption due to inconsistent results.

Table 10.
Monitoring and feedback mechanisms for RCA and RAP performance optimization.

environmental and mechanical stresses. Cloud-based systems and remote monitoring tools, such as drones, enable proactive adjustments and comprehensive assessments, ensuring the reliability and sustainability of RCA and RAP applications.

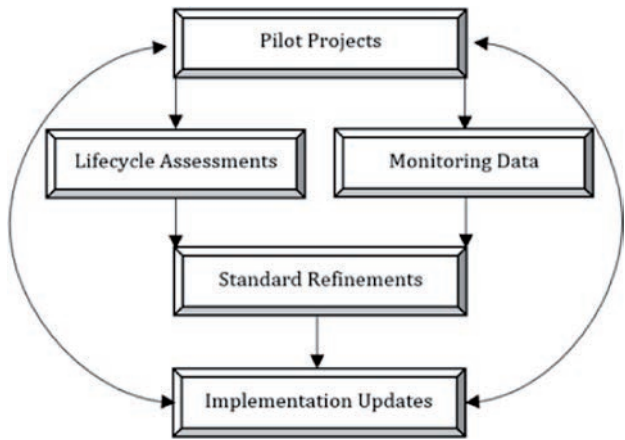


Figure 2.
Cyclical connections in the monitoring and feedback mechanisms for continuous improvement.

A robust monitoring framework supports continuous improvement in material performance while fostering stakeholder confidence. By dynamically refining standards and replicating successful practices, this approach accelerates the adoption of recycled materials, contributing to sustainability and resource efficiency in infrastructure projects. The cyclical nature of this system, as illustrated in **Figure 2**, ensures the integration of real-world insights into standards and practices, reinforcing the role of RCA and RAP in resilient construction.

5. Discussion and conclusion

This chapter has provided a comprehensive exploration of the role of Recycled Concrete Aggregates (RCA) and Reclaimed Asphalt Pavement (RAP) in fostering sustainable construction practices in Turkey. By evaluating their engineering properties, applicability under various environmental conditions, and potential in infrastructure projects, the discussion highlights the significant advantages of these materials in reducing Construction and Demolition Waste (CDW) and supporting circular economy principles in the construction sector.

The literature broadly agrees that RCA and RAP offer substantial environmental and economic benefits, particularly in reducing the demand for virgin aggregates, lowering greenhouse gas emissions, and improving waste management efficiency. Numerous studies confirm that RCA can successfully replace natural aggregates in non-structural applications, such as road base and subbase layers, without compromising mechanical integrity. Likewise, RAP is widely accepted as a cost-effective and sustainable alternative in asphalt mixtures, contributing to resource conservation and reduced energy consumption in pavement construction. However, there are disagreements regarding the long-term durability and engineering performance of RCA and RAP in high-stress environments. Some studies argue that RCA's high-water absorption and potential impurities may lead to strength variability, limiting its use in structural concrete applications. On the other hand, proper processing and quality control measures have been shown to significantly improve RCA performance, making it viable for broader infrastructure use. Similarly, while RAP is recognized for its sustainability advantages, concerns remain regarding its susceptibility to binder oxidation and aging effects, which could reduce long-term durability unless modified with polymer additives or rejuvenators. This study addresses these gaps by assessing the adaptability of RCA and RAP to Turkey's unique environmental conditions and infrastructure demands. The findings confirm that while these materials present a sustainable alternative to conventional aggregates, their performance is influenced by freeze-thaw cycles, high-temperature exposure, and traffic-induced stresses, requiring tailored modifications and quality assurance protocols.

The analysis has shown that RCA and RAP possess comparable mechanical properties to natural aggregates, making them viable alternatives for use in road bases, subbases, asphalt layers, and structural concrete applications. However, several key challenges remain, including material quality control, adaptation to local climatic conditions, and regulatory standardization. A significant limitation in the adaptation of RCA and RAP for large-scale implementation in Turkey has been the lack of a standardized framework to assess their performance in varying climatic conditions. The study highlights that freeze-thaw cycles and seismic activity are critical factors affecting the long-term durability of RCA-based materials. While RCA has demonstrated high compressive strength retention

(>90%) after 10 freeze-thaw cycles, variations in impurity levels and particle grading necessitate stricter quality control measures. Impurity thresholds below 5% have been identified as essential for maintaining material integrity, emphasizing the need for enhanced sorting, contamination control, and testing protocols in recycling plants.

Additionally, Turkey's diverse climate conditions, particularly extreme temperature fluctuations and high moisture levels, play a crucial role in influencing RAP performance. In high-temperature regions such as Southeastern Turkey (Gaziantep, Diyarbakır, and Şanlıurfa), where summer temperatures exceed 40°C, RAP-based asphalt formulations require modification with polymer additives or temperature-resistant bitumen to prevent rutting and premature deformation. Similarly, high-traffic corridors and urban road networks require additional compaction and mix optimization techniques to ensure long-term performance stability.

Despite these challenges, the research underscores the strong potential of RCA and RAP for integration into Turkey's road construction and infrastructure projects. A proposed standardized framework has been introduced to enhance the material collection, source separation, and quality assurance processes, ensuring consistent performance and compliance with national engineering standards. Strategies for overcoming implementation barriers, such as economic incentives, regulatory adaptation, and capacity-building programs, have also been outlined to facilitate large-scale adoption.

Pilot studies conducted in Istanbul, Ankara, and Izmir demonstrate that incorporating 30–50% RCA and RAP in infrastructure projects leads to significant benefits in terms of cost efficiency, environmental impact, and material performance. The results indicate that the use of recycled materials can reduce material procurement costs by 10–15% compared to conventional aggregates, making infrastructure projects more economically viable. Additionally, the adoption of RCA and RAP contributes to a 30% reduction in greenhouse gas emissions, thereby lowering the overall environmental footprint of construction activities. Furthermore, performance assessments show that RAP-based asphalt mixtures exhibit comparable rutting resistance to virgin asphalt, ensuring long-term durability and structural integrity in various road applications. These findings highlight the strong potential of RCA and RAP to support sustainable infrastructure development in Turkey while maintaining high engineering standards.

Furthermore, advanced lifecycle assessment (LCA) tools and feedback mechanisms enable engineers and policymakers to refine technical standards, optimize material use, and enhance sustainability outcomes. Full-scale implementation studies with real-world monitoring stations, digital tracking systems, and performance testing facilities are recommended to validate laboratory findings and optimize material formulations for regional adaptation.

By integrating recycled materials into national design codes, revising technical specifications, and expanding pilot projects, Turkey has the opportunity to establish itself as a leader in circular construction and resilient urban development. The findings of this study reinforce the critical role of RCA and RAP in achieving environmental, economic, and infrastructural sustainability, demonstrating that CDW can be transformed from a challenge into a valuable resource.

In conclusion, this chapter provides a science-based roadmap for the successful adoption of recycled materials in Turkey's construction sector. By implementing the proposed strategies, stakeholders—including municipalities, engineers, contractors, and policymakers—can contribute to a sustainable and innovative built environment.

These efforts align with global sustainability goals while addressing Turkey's unique infrastructural and environmental challenges, fostering a more efficient, cost-effective, and eco-friendly construction industry for future generations.

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Conflict of interest

The authors declare no conflict of interest.

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References

- [1] Karademir M, Özbakir BA. Environmental Pollution Analysis From Urban Transformation and Construction and Demolition Waste Management: Istanbul Kadikoy Case Study, International City Planning and Design Conference CPUD'18. İstanbul, Turkey; 2018:108-122
- [2] Arslan V, Ulubeyli S. Sorting at source and reusing: The case of construction and demolition waste in Turkey. *Journal of Construction Engineering, Management & Innovation*. 2019;2:230-236
- [3] Beldek T, Camgöz-Akdağ H, Hoşkara E. Green supply chain management for construction waste: Case study for Turkey. *International Journal of Sustainable Development and Planning*. 2016;11(5):771-780
- [4] Yılmaz T, Ercikdi B, Deveci H. Utilisation of construction and demolition waste as cemented paste backfill material for underground mine openings. *Journal of Environmental Management*. 2018;222:250-259
- [5] Beja IA, Motta R, Bernucci LB. Application of recycled aggregates from construction and demolition waste with Portland cement and hydrated lime as pavement subbase in Brazil. *Construction and Building Materials*. 2020;258:119520
- [6] Bilgili L, Çetinkaya AY. Environmental impact assessment of earthquake-generated construction and demolition waste management: A life cycle perspective in Turkey. *Environment Systems and Decisions*. 2024;44(2):424-432
- [7] Istanbul Metropolitan Municipality. Istanbul metropolitan municipality official website. n.d. Available from: <https://ibb.istanbul/en/> [Accessed: January 3, 2025]
- [8] Koçak AB, Soyluk A, Ayçam İ. The environmental impact of reusing post-earthquake demolition waste: İskenderun case study. *Gazi University Journal of Science*. 2024;37(3):1042-1054
- [9] Mavroulis S, Mavrouli M, Vassilakis E, Argyropoulos I, Carydis P, Lekkas E. Debris management in Turkey provinces affected by the 6 February 2023 earthquakes: Challenges during recovery and potential health and environmental risks. *Applied Sciences*. 2023;13(15):8823
- [10] Uğurlu Aİ, Karakoç MB, Özcan A. Effect of binder content and recycled concrete aggregate on freeze-thaw and sulfate resistance of GGBFS based geopolymer concretes. *Construction and Building Materials*. 2021;301:124246
- [11] Akbas M, İyisan R, Dayioğlu AY, Hatipoğlu M. Stiffness properties of recycled concrete aggregates as unbound base and subbase materials under freeze and thaw cycles. *Arabian Journal for Science and Engineering*. 2021;46(11):10569-10584
- [12] Bayraktar OY, Soylemez H, Kaplan G, Benli A, Gencil O, Turkoglu M. Effect of cement dosage and waste tire rubber on the mechanical, transport and abrasion characteristics of foam concretes subjected to H₂SO₄ and freeze-thaw. *Construction and Building Materials*. 2021;302:124229
- [13] Akbaş M, İyisan R. Freeze and thaw effect on the stiffness properties of recycled concrete aggregate used in the road embankment. *Journal of the Faculty of Engineering and Architecture of Gazi University*. 2021;36(2):971-984

- [14] Toka EB, Olgun M. Performance of granular road base and sub-base layers containing recycled concrete aggregate in different ratios. *International Journal of Pavement Engineering*. 2022;**23**(11):3729-3742
- [15] Bayraktar OY, Kaplan G, Benli A. The effect of recycled fine aggregates treated as washed, less washed and unwashed on the mechanical and durability characteristics of concrete under MgSO_4 and freeze-thaw cycles. *Journal of Building Engineering*. 2022;**48**:103924
- [16] Tarhan Y, Şahin R. Use of recycled aggregate concretes in road and site concretes subject to freeze-thaw effect. *Journal of Studies in Advanced Technologies*. 2023;**1**:2
- [17] Toka EB, Olgun M. Mechanical and economic evaluation of recycled concrete aggregate as granular road base and subbase material. *Journal of Materials in Civil Engineering*. 2023;**35**(5):04023097
- [18] Aytekin B, Mardani A, Ünsever YS. Performance assessment of recycled waste materials for use in unbound pavement layers: A case study from Turkey. *Construction and Building Materials*. 2023;**402**:133004
- [19] Ulucan M, Alyamac KE. A comprehensive assessment of mechanical and environmental properties of green concretes produced using recycled concrete aggregates and supplementary cementitious material. *Environmental Science and Pollution Research*. 2023;**30**(43):97765-97785
- [20] Gul WA. Effect of recycled cement concrete content on rutting behavior of asphalt concrete [Master's thesis]. Ankara, Turkey: Middle East Technical University; 2008
- [21] Sengoz B, Topal A, Oner J, Yilmaz M, Dokandari PA, Kok BV. Performance evaluation of warm mix asphalt mixtures with recycled asphalt pavement. *Periodica Polytechnica Civil Engineering*. 2017;**61**(1):117-127
- [22] Seferoğlu AG, Seferoğlu MT, Akpınar MV. Investigation of the effect of recycled asphalt pavement material on permeability and bearing capacity in the base layer. *Advances in Civil Engineering*. 2018;**2018**(1):2860213
- [23] Seferoğlu AG, Seferoğlu MT, Akpınar MV. Investigating the mechanical behavior of reclaimed asphalt pavement (RAP) bases in large scale test box. *Teknik Dergi*. 2019;**30**(6):9581-9596
- [24] Abut Y, Yildirim ST. An investigation on the durability properties of RAP-containing roller compacted concrete pavement. *European Journal of Environmental and Civil Engineering*. 2022;**26**(2):802-818
- [25] Fenerci K, Erdoğan MC, Abut Y. The economic potentials of reclaimed asphalt pavements (RAP) in urban road infrastructure: A case study of Yalova city. *Journal of Innovative Engineering and Natural Science*. 2023;**3**(2):205-218
- [26] Kaya O. Experimental investigation of usability of 100% recycled asphalt pavement (RAP) as a cold patching material in Turkey. *Karadeniz Fen Bilimleri Dergisi*. 2023;**13**(1):223-231
- [27] Uygunoğlu T, Topçu İLKER, Çınar Resuloğulları E. Durability effect of reclaimed asphalt aggregate on concrete road pavement. *Materiales de Construcción*. 2024;**74**(353)
- [28] Dokuzlar G, DüNDAR B, Yurt Ü. Effect of recycled asphalt waste on mechanical properties of alkali-activated mortars. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*. 2024;**238**(4):1851-1859

- [29] Algin HM, Turgut P. Cotton and limestone powder wastes as brick material. *Construction and Building Materials*. 2008;**22**(6):1074-1080
- [30] Altuncu D, Kasapseçkin MA. Management and recycling of constructional solid waste in Turkey. *Procedia Engineering*. 2011;**21**:1072-1077
- [31] Bilgin N, Yeprem HA, Arslan SÖNMEZ, Bilgin A, Günay E, Marşoglu M. Use of waste marble powder in brick industry. *Construction and Building Materials*. 2012;**29**:449-457
- [32] Atan E, Sutcu M, Cam AS. Combined effects of bayer process bauxite waste (red mud) and agricultural waste on technological properties of fired clay bricks. *Journal of Building Engineering*. 2021;**43**:103194
- [33] Karslioğlu A, Balaban E, Onur Mİ. Insulation properties of bricks with waste rubber and plastic: A. *Journal of Nature*. 2021;**1**:20-27
- [34] Ulugöl H, Günal MF, Yaman İÖ, Yıldırım G, Şahmaran M. Effects of self-healing on the microstructure, transport, and electrical properties of 100% construction-and demolition-waste-based geopolymer composites. *Cement and Concrete Composites*. 2021;**121**:104081
- [35] Erdogmus E, Yaras A, Sutcu M, Gencel O. Recycling of marble cutting waste additives in fired clay brick structure: A statistical approach to process parameters. *Environmental Science and Pollution Research*. 2022;**29**(47):71936-71947
- [36] Uysal M, Aygörmez Y, Canpolat O, Cosgun T, Kuranlı ÖF. Investigation of using waste marble powder, brick powder, ceramic powder, glass powder, and rice husk ash as eco-friendly aggregate in sustainable red mud-metakaolin based geopolymer composites. *Construction and Building Materials*. 2022;**361**:129718

Section 3

Future Infrastructure Challenges and Opportunities

Cool Pavements for the Mitigation of Urban Heat Island (UHI): A Global Perspective

Domenico Vizzari, Paulina Leiva-Padilla and Hengwu Hu

Abstract

The human activities such as burning of fossil fuels, deforestation, and industrial processes, which release greenhouse gases (GHGs) such as carbon dioxide, methane, and nitrous oxide into the atmosphere, are the primary drivers of climate change. As a consequence, the average surface temperature is continuously increasing. In urban areas, this phenomenon is more pronounced, contributing to the urban heat island (UHI) effect, which directly impacts the health of vulnerable populations and the increase in energy consumption. At present, among the most common measures applied to contrast the heat island effect are cool and energy harvesting pavements. This chapter starts with a summary of UHI intensity data for various cities around the world, highlighting cool pavements as the most promising solutions. Then, for each technology, the working principles and governing equations are detailed. The objective of this chapter is to analyze the state of the art in cool pavement technologies and provide a critical assessment of each solution in terms of advantages, disadvantages, and effectiveness in mitigating the urban heat island effect. The review adopts an integrative approach by: identifying the most significant research addressing working principles, modeling, and UHI mitigation and assessing, critiquing, and synthesizing the literature to identify frameworks and future perspectives. In conclusion, reflective pavements are strong candidates for simple, effective, and low-cost UHI mitigation, while energy-harvesting pavements remain promising technologies that combine heat island mitigation with the ability to capture thermal energy. However, their widespread adoption is still limited by prohibitive initial costs.

Keywords: urban heat island (UHI), climate change, reflective pavement, permeable pavement, energy harvesting pavement

1. Introduction

Nowadays, burning fossil fuels, deforestation, and livestock farming are the main causes of climate change. Global warming is continuously increasing at a rate of 0.2°C every 10 years [1]. Notably, the decade from 2011 to 2020 was the warmest ever recorded. The rise in temperature also directly impacts the average surface temperature. The World Meteorological Organization [2] estimated that the global average surface temperature was 1.44°C higher than the 1850–1900 average.

In urban areas, this phenomenon is more pronounced and is known as the urban heat island (UHI) effect. Urban overheating affects more than 400 major cities worldwide, with average temperature increases between 4°C and 5°C, and peaks up to 10°C [3]. The EPA defines the UHI as urbanized areas that experience higher temperatures than outlying areas. The UHI (ΔT_{u-r}) intensity is given by the expression [4]:

$$\Delta T_{u-r} = T_u - T_r \quad (1)$$

where T_u is the urban temperature and T_r the rural temperature. **Figure 1** collects the UHI intensity for different cities around the world. The general tendency shows maximum UHI values between 6°C and 9.5°C, which reflect between 2 and 3 more intense UHI at certain moments of the day in reference to the average value for all the cities.

The UHI is not just due to the presence of infrastructure, roads, and buildings enhancing the absorption of solar radiation but also because of the heat from fuel combustion, the low albedo of certain surfaces (i.e., asphalt pavement [13]), accumulation of solar energy during the day, and release at night due to changes in the thermophysical properties of the urban underlying surface [14].

UHI reaches its maximum overnight, in clear sky, due to longwave emission at nighttime from daytime heat [6]. The UHI affects the livability of cities, and it:

- increases cooling energy demand, water consumption, and associated costs;
- affects CO₂ emissions [15];
- contributes to the degradation of air quality due to the formation of smog and air pollutants;

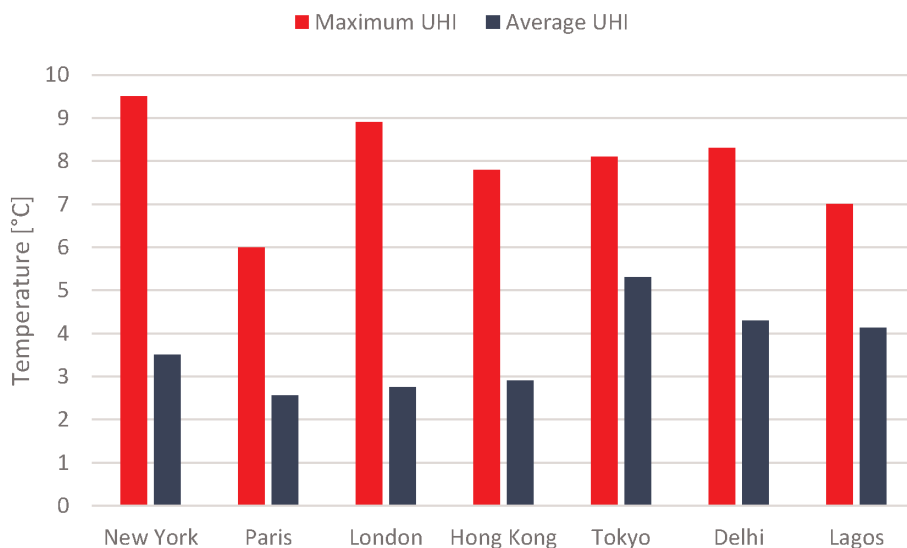


Figure 1. Maximum and average UHI in New York [5, 6], Paris [7], London [8], Hong Kong [9, 10], Tokyo [7], Delhi [7], and Lagos [11, 12].

- impacts urban ecosystems and the living environment;
- modifies the local climate due to friction with structures and channeling through streets [16];
- affects people suffering from existing minor conditions; and
- increases the risk of hospitalization and death [17].

Roxon et al. [18] calculate that 2°C of temperature rise causes a 40% increase in UHI energy costs, while 1°C decrease causes a 46% reduction. Gago et al. [19] define six parameters affecting the UHI:

1. the green plot ratio, representing the ratio of green space to the total plot area in a given urban zone [20];
2. the sky view factor (SVF), given by the ratio of the visible sky area of a point in space to the total sky area [21];
3. the building density, representing the ratio between the building surface and a given urban area [22];
4. the wall surface;
5. the pavement surface;
6. the albedo, defined as the percentage of incident solar radiation that is reflected by a surface [23].

At present, the most effective strategies to mitigate the UHI include the implementation of parks and green spaces, green roofs, urban ventilation systems, and cool pavements. Parks and green areas enhance the microclimate through evapotranspiration, a process where trees absorb water through their roots and release it as water vapor into the atmosphere, thereby reducing ambient temperatures. This cooling effect can lower temperatures by 0.5–4°C. For instance, parks larger than 10 hectares can reduce the temperature by 1–2°C within a 350-m radius. Similarly, green roofs help to decrease roof temperatures through evapotranspiration, contributing to thermal comfort inside buildings. These roofs provide excellent thermal insulation, comparable to an extruded polystyrene panel approximately 80–90 mm thick. Additionally, the soil and plant roots can retain rainwater, aiding in stormwater management while also enhancing the urban aesthetic and supporting biodiversity.

Urban ventilation mitigates the UHI thanks to the flow of air from rural areas into the city. This airflow creates mechanical turbulence along primary diffusion roads, improving convective heat exchanges with buildings and infrastructure. Cool pavements counteract the UHI thanks to their lower temperature in comparison to conventional road materials. Cool pavements are distinguished as reflective, permeable, and energy harvesting. Reflective pavements reduce outdoor temperature thanks to the absorption of lower solar radiation through reflective paints/coatings with high solar reflectance. Permeable pavements reduce surface temperature thanks to the evaporation of water infiltrated in a porous layer, contributing additionally to urban

stormwater management. Energy harvesting pavements convert radiation into electricity by means of solar cells (i.e., solar pavement [24]), or store excess heat by means of a calorific fluid (i.e., asphalt solar collector [25]).

This study follows an “integrative review” methodology, which additional to summarize information from different sources, allows for the assessment, critique to provide new perspectives.

The literature selection process consists of gathering comprehensive information on several key aspects such as working principles, governing equations, and UHI mitigation impacts (on air and surface temperatures) [26].

The topic is relevant because UHI effect is a common problem in the process of rapid urbanization. The aim of this paper is not only limited to explain the working principles of cool pavements but also to identify advantages and disadvantages of existing solutions. This approach ensured a thorough understanding of the theoretical foundations and practical implications of cool pavement technology in addressing UHI effects.

2. Working principle

2.1 Reflective pavement

Reflective pavements exhibit higher albedo compared to conventional pavements with relatively low albedo. As shown in **Figure 2**, the dominant heat transfer modes are radiation and convection at the top layer, and conduction through the different road layers.

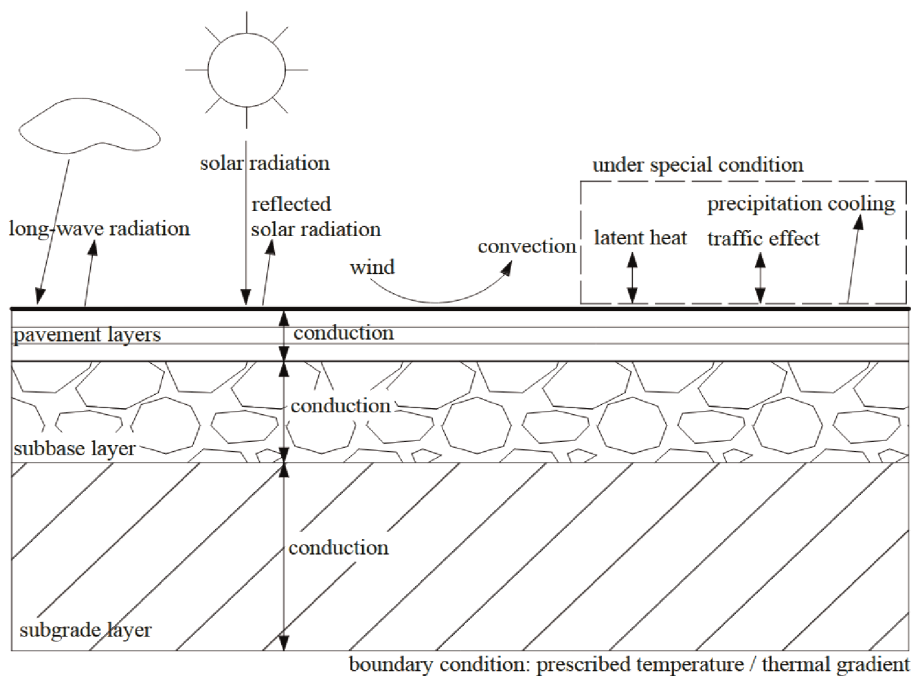


Figure 2.
Heat transfer modes pavement vs. environment [27].

Assuming constant thermal conductivity and the pavement as a layered structure, the transient heat flow is expressed by the one-dimensional differential equation as follows [28]:

$$\frac{k_i}{\rho_i c_i} \frac{\partial^2 T_i(z, t)}{\partial z^2} = \frac{\partial T_i(z, t)}{\partial t} \text{ for } x_{i-1} < x < x_i; t > 0 \quad (2)$$

where:

- $T_i(z, t)$ is the temperature of the i-th layer;
- z is the pavement height;
- t is the time;
- k_i is the thermal conductivity of the i-th layer (W/mK);
- ρ_i is the density of the i-th layer (kg/m³);
- c_i is the specific heat capacity of the i-th layer.

Moving from the hypothesis that temperature and heat flux are both continuous at each interface between layers, the following relations can be written:

$$T_i(z, t)|_{z=z_i} = T_{i+1}(z, t)|_{z=z_i} \quad (3)$$

$$k_i \frac{\partial T_i(z, t)}{\partial z} \Big|_{z=z_i} = k_{i+1} \frac{\partial T_{i+1}(z, t)}{\partial z} \Big|_{z=z_i} \quad (4)$$

The magnitude of heat flow depends on intrinsic factors (i.e., thermal properties of the materials) and extrinsic factors (i.e., meteorological conditions). The heat exchange at the surface is the result of different thermal fluxes, affected by the external environment. The interaction between pavement and environment is described through the following energy balance at the surface (for $z = 0$) [29]:

$$k_1 \frac{\partial T_1(z, t)}{\partial z} \Big|_{z=0} = Q_{ns} - Q_{nl} - Q_c - Q_E \pm Q_v - Q_p \quad (5)$$

where:

- Q_{ns} is the net solar radiation absorbed by the surface;
- Q_{nl} is the net longwave radiation;
- Q_c is the heat flux due to convection;
- Q_E is the heat flux due to evaporation;
- Q_v is the heat energy flux due to the passage of vehicles;
- Q_p is the cooling effect due to surface runoff (due to water flow on the pavement surface).

More in detail, Q_{nl} [27] is the net longwave radiation between pavement and environment. Under the assumption that the ambient surrounding is isothermal with a much larger surface area, Q_{nl} is given by:

$$Q_{nl} = \varepsilon \sigma (T_s^4 - T_{\infty K}^4) \quad (6)$$

With:

- ε is the surface emissivity;
- σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$);
- T_s is the pavement surface temperature (K);
- $T_{\infty K}$ is the ambient temperature (K).

Q_C is the heat transfer between air and pavement surface. The heat flow is expressed as follows:

$$Q_C = -h(T_s - T_a) \quad (7)$$

$$h = \frac{N_u k}{L} \quad (8)$$

where:

- h is the convection coefficient;
- T_s is the surface temperature;
- T_a is the air temperature;
- k is the material's thermal conductivity;
- N_u is the Nusselt number (determined by empirical correlations depending on the type of convection and the flow regime).

The heat flux due to evaporation (Q_E) is influenced by the moisture at the surface and by the vapor density difference between pavement surface and air [30]:

$$Q_E = \lambda h_e \frac{\rho_a - \rho_{sat}}{r_s} \quad (9)$$

where:

- λ is the enthalpy of vaporization of water ($2260 \times 10^3 \text{ J/kg}$);
- ρ_a and ρ_{sat} are vapor and saturated vapor density of the air (kg/m^3), respectively;
- h_e is the evaporative heat-transfer coefficient relative to wind speed;
- r_s (s/m) is defined as the bulk evaporative resistance and represents the water vapor diffusion from the source to the air immediately above the pavement.

$$r_s = ae^{b\theta} \quad (10)$$

More in detail, a and b are two regression coefficients. When the water content (θ) decreases, b is negative because the surface resistance increases, and further evaporation is suppressed.

Q_{traffic} depends on the traffic density (D_{veh} , vehicles/s); the average vehicle speed (v_{veh} , m/s); the impact of the traffic area (S_{impact}), representing the road width; and the heat flux of a vehicle (Q_v , assumed to be 3903 J per vehicle per second at a specific average vehicle speed) [29]. The governing equation is given by:

$$Q_{\text{traffic}} = \frac{1}{S_{\text{impact}}} \frac{1}{v_{\text{veh}}} D_{\text{veh}} Q_v \quad (11)$$

Q_p , also called sensible heat due to precipitation, is defined as [31]:

$$Q_p = C_w \rho_w R (T_0 - T_w) \quad (12)$$

where:

- C_w is the specific heat of rain (around 4186 J/kg K);
- ρ_w is the density of rain (kg/m³),
- R is the rain rate (m/s);
- T_0 is the temperature of the road (K);
- T_w is the temperature of the raindrops at the surface (K).

Q_{sw} depends on the solar irradiation I and the albedo surface r as expressed in [29]:

$$Q_{sw} = I(1 - r) \quad (13)$$

In general, reflective pavement attenuates the surface temperature thanks to the higher albedo. As a consequence, most of the solar radiation is reflected back to the sky. **Table 1** shows some typical values of albedo for different types of pavements/surfaces:

2.2 Permeable pavement

Permeable pavements are multilayered systems designed to mitigate flooding by allowing water infiltration and improving stormwater management. Typically, these pavements are associated with the use of porous concrete or asphalt, and more recently with the use of waste materials, and adapted design methods to propose sustainable and environmental pavement structures [13].

As shown in **Figure 3**, permeable pavements are typically composed of [34]:

- A surface permeable layer (porous asphalt, permeable concrete, interlocking pavers, or grid systems), where the rainwater falls and infiltrates through the porous surface.

Pavement type	Albedo	Ref.
Conventional friction course	0.04–0.1	[13]
Aged friction course	0.09–0.18	[13]
Recycled asphalt concrete, containing exhausted extinguishing powders	0.12–0.13	[13]
Rubberized hot mixed asphalt	0.08–0.09	[32]
Rubberized warm mixed asphalt	0.06–0.07	[32]
New cement concrete	0.18–0.36	[27]
New cement concrete (gray)	0.12–0.40	[27]
New cement concrete (white)	0.6–0.8	[27]
Aged cement concrete	0.18–0.35	[27]
Aged cement concrete (gray)	0.20–0.30	[27]
Aged cement concrete (white)	0.40–0.60	[27]
Pervious cement concrete	0.25–0.35	[27]
Gravel	0.15–0.20	[32]
Grass	0.25–0.3	[33]
Fresh snow	0.81–0.88	[33]

Table 1.
Typical values of albedo for different types of pavements.

- A water retention or filter layer: permeable base and subbase layers, composed of high-porosity aggregates and act as a temporary reservoir to retain and/or filter water.
- An infiltration or controlled drainage layer: subsoil and drainage system depending on the soil permeability. For a full infiltration, the water is completely absorbed into the underlying soil, and in the partial or null infiltration, part or the totality of water is directed to a drainage system or percolated to the aquifers.

The movement of water through unsaturated porous media is a complex process governed by the interactions between water, air, and the solid matrix. Permeable pavement working principles involve a multidisciplinary approach that integrates hydraulics, geotechnics, and pavement engineering. As described in Eq. (14), for an unsaturated porous medium, the rate of change in water mass within a control volume is equal to the net flux divergence of water entering and leaving the volume, following the principle of mass conservation [35]:

$$\partial m_w / \partial t + \nabla \cdot (\rho_w q_w) = 0 \quad (14)$$

where m_w represents the mass of water, ρ_w is the water density, and q_w is the volumetric flow vector of water. Assuming the incompressibility of water, the hydraulic flow can be described by Darcy's law. Under this assumption, Eq. (14) can be transformed into Eq. (15).

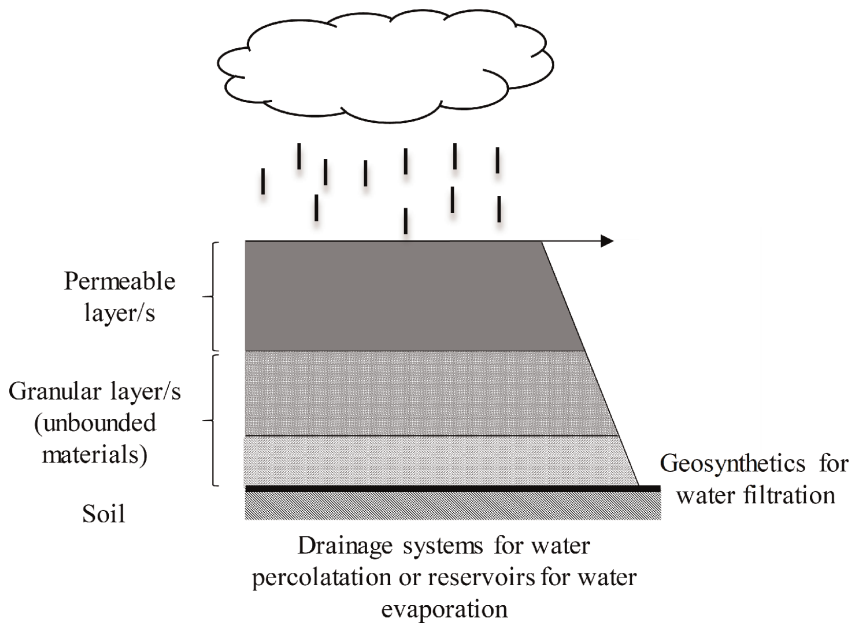


Figure 3.
 Permeable pavement composition.

$$\frac{C_w \partial \Psi_w}{\partial t} = \nabla \cdot (K_w \nabla \Psi_w) \quad (15)$$

where:

- $\nabla \Psi_w$ represents the gradient of the hydric potential;
- K_w is the hydraulic conductivity, which depends on the soil moisture content and hydraulic properties;
- C_w is the specific water capacity, which describes how water retention in soil pores changes as a function of the hydric potential.

Water moves following energy gradients defined by the hydraulic potential that represents the energy state of water at a given location relative to a reference point. As shown in Eq. (16), this potential is composed of the matric potential (Ψ_m), related to capillary forces and water adhesion to the solid matrix, which is negative in unsaturated media and zero in saturated conditions; the gravitational potential (Ψ_g), which depends on the elevation of the point of interest relative to a reference height; and the pressure potential (Ψ_p) related to the hydrostatic pressure exerted by water columns in saturated conditions but is negligible in unsaturated media.

$$\Psi_w = \Psi_m + \Psi_g + \Psi_p \quad (16)$$

As shown in Eq. (17), in unsaturated porous media, the hydraulic potential simplifies to:

$$\Psi_w = \Psi_m p_w g \gamma \quad (17)$$

where:

- g is gravitational acceleration;
- y is the elevation of the water relative to the reference point.

As shown in Eq. (18), the combination of the mass conservation equation with the definition of hydraulic potential leads to Richards' equation, which describes how water redistributes within a porous medium based on retention and conductivity properties.

$$\frac{C_w \partial \Psi_w}{\partial t} = \nabla \cdot (K_w (\nabla \Psi_w + p_w g \nabla y)) \quad (18)$$

The parameter C_w describes how the material retains water and is given by, the porosity (ϕ), representing the fraction of void spaces that can be filled with water, and the saturation degree (S_w), which indicates the proportion of pores occupied by water.

$$C_w = \phi \partial S_w / \partial \Psi_w \quad (19)$$

As shown in Eq. (20), the hydraulic conductivity term (K_w), essential for describing water flow. It depends on the relative permeability (k_{rw}), the intrinsic permeability of the material (k_{int}), a constant dependent on its structure, and the dynamic viscosity of water (μ_w), which varies between 0 in dry conditions and 1 in fully saturated conditions.

$$K_w = \frac{k_{rw} k_{int}}{\mu_w} \quad (20)$$

In practical applications, the volumetric flow is expressed in terms of the hydraulic head gradient (H_w , Eq. (21)).

$$H_w = \frac{\Psi_w}{p_w g} \quad (21)$$

The hydraulic head gradient allows a direct comparison between water flow in unsaturated and saturated conditions. The relationship between hydraulic conductivity and intrinsic permeability can also be rewritten as in Eq. (22) or, in terms of intrinsic permeability, as in Eq. (23).

$$K_H = p_w g K_w \quad (22)$$

$$K_H = \frac{p_w g k_{rw} k_{int}}{\mu_w} \quad (23)$$

For the design, maintenance, and effectiveness of these types of pavements, hydraulic conductivity and freeze-thaw cycles in cold regions must be taken into account. Furthermore, the open-graded granulometry of the surface layer tends to clog over time. As a result, roads exposed to heavy traffic loads, parking lots, or access roads may not be suitable for use as permeable pavements [36, 37].

The evaluation of permeable pavement performance involves a variety of methods [38], including permeability tests to characterize infiltration rates; leachate analysis to quantify metals, oils, polycyclic aromatic hydrocarbons (PAHs), pH, conductivity, and nutrients; computed tomography (CT) scans to describe pore structure and fine

particle distribution; and structural and material performance tests to assess the effects of moisture content (bearing capacity for permeable subbase materials, freeze-thaw cycles, soundness tests).

2.3 Energy harvesting pavement

Energy harvesting pavements can convert solar radiation or traffic load into useful energy. Solar radiation is converted into electricity by means of solar cells protected by a semitransparent layer, or it is stored by means of a calorific fluid circulating through asphalt solar collectors or a porous medium. Furthermore, the heat of the pavement can be exploited using thermoelectric generators (TEGs).

The photoelectric conversion mechanism of solar roads converts a portion of solar radiation into electricity, rather than absorbing and releasing it. As a consequence, the pavement exhibits a slightly lower temperature. In light of this, the equation can be written as:

$$Q_{sw} = I(1 - r - s_{photo}) \quad (24)$$

with s_{photo} representing the portion of solar radiation converted into electricity thanks to the photovoltaic effect.

Asphalt solar collectors are pipes embedded into the asphalt for the circulation of a calorific fluid. Sunlight is first absorbed by the asphalt surface, causing the pavement temperature to increase, leading to a conduction mechanism from the surface to the lower layers. Conduction also involves the asphalt-pipes interface. Finally, heat is transferred to the calorific fluid through convection between the collector and fluid.

The amount of harvested heat by the asphalt solar collector is governed by the mass flow rate ($\dot{m}_w$) of the pump and the fluid temperatures in the tubes [39]:

$$Q = \dot{m}_w c_p (T_{wo} - T_{wi}) \quad (25)$$

where T_{wo} and T_{wi} are the fluid temperatures at the outlet and inlet, respectively.

Road thermoelectric generator systems exploit the heat of the pavement to generate electricity by means of thermoelectric modules embedded into the asphalt. Similarly to the previous equation, at the interface between road and environment, a small portion of solar radiation contributes to the heating of the TEG (s_{TEG}). Consequently, the surface temperature is slightly lower.

$$Q_{sw_TEG} = I(1 - r - s_{TEG}) \quad (26)$$

Hasebe et al. [40] coupled TEGs with an asphalt solar collector, exploiting river water as a cold source. Wu and Yu [41] built a prototype composed of an aluminum plate and a rod installed in a hole drilled along an asphalt sample. The TEG module was located on the aluminum plate. The other end of the rod was placed on dry sand to simulate the subgrade soil.

3. Urban heat island mitigation by means of cool pavements

As previously described, cool pavements—including reflective, permeable, and energy-harvesting structures—have been proposed as effective strategies to mitigate the urban heat island effect. To synthesize the current state of knowledge, the

following sections present and analyze the most relevant findings reported in scientific literature regarding these alternative pavement technologies.

3.1 Reflective pavement for the urban heat island mitigation

Compared with the black asphalt pavement laid by traditional techniques, reflective pavement materials, due to their weaker ability to absorb solar radiation, can effectively reduce the accumulation of solar heat, keeping the internal temperature of the pavement structure at a relatively low level and thus decreasing the occurrence probability of high-temperature distresses such as rutting and shoving [42]. The factors influencing the cooling effect of reflective pavements include fillers (optical properties, particle size, and volume fraction), environmental factors (light intensity, air humidity, and wind speed), and coatings (color, thickness, and structure) [43]. These three types of factors work synergistically to form a multidimensional influencing pathway, and comprehensive consideration is required in engineering applications to achieve the optimal cooling effect.

Li et al. [32] demonstrated that for every 0.1 increase in the reflectivity index of pavement materials, a reduction of approximately 0.6°C in the maximum surface temperature of the pavement could be observed during the summer season. You et al. [44] employed flake-shaped CuO nanoparticles as reflective functional materials to fabricate a black near-infrared reflective coating. When the mass fraction of CuO nanoparticles was 22.6%, the reflectivity in the near-infrared region could reach 40.5%, enabling a reduction of approximately 13°C in the surface temperature of asphalt pavements during hot summer weather.

Thermochromic pavement materials have been proposed by scholars as a solution to address the limitations of traditional heat-reflective coatings. While heat-reflective coatings can effectively reduce pavement temperatures during summer, they may exacerbate air temperature reduction in winter, thereby increasing heating demands and impeding normal social activities. Thermochromic materials, as a type of coating with dynamic optical properties, can automatically adjust their reflectivity in response to changes in ambient temperature or solar radiation intensity [45]. The ability of thermochromic materials to alter their albedo in response to surface temperature variations is attributed to their thermally reversible molecular structural transformations, which induce changes in the visible color spectrum. Hu et al. [46] designed a thermochromic coating to regulate the surface temperature of asphalt pavements. Experimental results demonstrated that during high temperatures, the reflectivity of the thermochromic coating exceeded that of conventional asphalt concrete pavements, with a maximum temperature reduction of up to 6.6°C on the coated pavement under hot weather conditions. Conversely, in cold weather, the surface temperature of asphalt concrete coated with the thermochromic material was generally 1°C higher than that of uncoated asphalt concrete. Despite the commercialization of thermochromic materials in related fields [47], their high cost remains a significant barrier to widespread application in specific areas such as pavement engineering.

Pavement reflective coatings not only can significantly reduce the temperature of the pavement structure itself but also effectively lower the near-surface air temperature, thereby enhancing pedestrian thermal comfort and reducing the cooling energy consumption of adjacent buildings during hot seasons.

Santamouris et al. conducted a study in which they replaced low-reflectivity pavement materials (with the solar reflectance of most original ground materials ranging from 0.35 to 0.45, and that of cement concrete pavements and asphalt concrete

pavements only between 0.11 and 0.21) covering an area of 4500 m² in the Flisvos Urban Park area in southwestern Greece with high-reflectivity colored cement concrete blocks (having a solar reflectance of approximately 0.6). The study findings indicated that the maximum summer air temperature within the park could be reduced by 1.9°C, with a decrease in surface temperature of up to 12°C [48].

Mohegh et al. [49] carried out a 1-year simulation study in California, and the results indicated that when the reflectivity of urban roads in California was increased by 0.4, the near-surface air temperature experienced a decrease ranging from 0.18°C to 0.86°C. Carnielo et al. [50] conducted a simulation study in Rome, which revealed that when the ground surface was changed from regular asphalt concrete pavement to a light gray-coated asphalt pavement, the near-surface air temperature (3 m above the road surface) decreased by an average of 5.5°C. Concurrently, the peak cooling energy demand of an adjacent four-story residential building was reduced from 21.2 to 17.2 kW, marking an 18.9% decrease.

Additionally, phase change materials (PCMs) can be incorporated as fillers into heat-reflective coatings. Liu et al. [51] developed a montmorillonite/stearic acid composite PCM, which was combined with titanium dioxide as a filler to achieve a synergistic cooling effect through both phase change and reflection. Experimental results demonstrated that this coating exhibited remarkable cooling performance, with an average indoor temperature reduction of 24.8°C and an average outdoor temperature reduction of 7.29°C.

Although the newly developed reflective coatings possess excellent optical properties, in practical applications, pavement cooling coatings must withstand repeated friction from vehicle wheel loads. Under continuous wheel loading, the coating materials experience wear, leading to material loss and a reduction in the cooling efficiency of the pavement coating. Studies have shown that durability loss within 1 year can result in a 13–53% decrease in cooling effectiveness and a 50% reduction in reflectivity [52]. Insufficient wear resistance of the coatings has become a critical bottleneck restricting the widespread adoption of pavement reflective cooling coatings. Additionally, the use of coatings can significantly impact the pavement's skid resistance and glare characteristics, which necessitates careful consideration in engineering practices.

In summary, although current studies have made progress, there are geographical limitations and climate-dependent deficiencies, and there is an urgent need to supplement the comparative data from different climatic zones in order to strengthen the generalizability of the study. If the maintenance or material costs are higher than the energy-saving benefits, the sustainability of reflective pavements is doubtful, and an energy-economic balance model should be introduced to evaluate the whole life cycle cost-effectiveness. In addition, the existing studies focus on a single dimension, temperature, and do not consider the impact of glare on the thermal comfort and visual safety of pedestrians, and need to be combined with PET, UTCI, and other comprehensive indicators to carry out a multi-dimensional assessment.

3.2 Permeable pavement for the urban heat island mitigation

Permeable pavements allow rainwater to infiltrate reducing surface runoff and promoting evaporation which cools the surrounding air. Maximum daily road surfaces can be reduced by 3.4°C for surface permeable pavements and 4.3°C for fully permeable pavements under dry conditions [53]. The inclusion of water storage and drainage systems can enhance permeable pavements' cooling effects. Butler et al. [54]

found an average cooling effect of 1°C reaching up to 5°C as maximum when the pavement is actively watered.

Field studies [55, 56] including grass coverage revealed reductions in mean air temperatures by 1.18°C and up to 1.26°C.

Also, materials with higher permeability and lower thermal conductivity that allow water infiltration and reduce heat transfer [57, 58] can influence the cooling performance of permeable pavements, as well as environmental conditions as temperature, wind speed, relative humidity, and the presence of water in general [58, 59].

In summary, permeable pavements offer a promising solution for urban heat island mitigation through evaporative cooling and stormwater management. However, their practical application is currently limited by technical challenges, including reduced mechanical strength due to high porosity, sensitivity to humidity, and performance degradation caused by pore clogging. Current research is focused on filling these research gaps by improving water retention materials and enhancing the balance between thermal effectiveness and structural integrity. Addressing issues related to durability, cost, and integration with existing pavement systems remains essential for their large-scale implementation.

3.3 Energy harvesting pavement for the urban heat island mitigation

The primary characteristic of energy harvesting pavements is their ability to generate electricity and/or store thermal heat. The reduction of surface and air temperature is a consequence of the energy conversion. Among solar roads, studies have shown that they can mitigate the surface temperature of pavements by 3–5°C compared to conventional asphalt mixtures [60]. This reduction is primarily attributed to the conversion of a portion of incident solar radiation into electrical energy, thereby decreasing the amount of heat absorbed and re-radiated by the road surface [61].

The impact of solar roads on air temperature is less pronounced but still notable (nearly 1°C). While this reduction may seem modest, it can have significant implications for urban microclimate, especially when implemented on a large scale.

Asphalt solar collectors have the highest potential in reducing surface temperatures. These systems can achieve a surface temperature reduction of 10–20°C [62]. The impact of asphalt solar collectors is also significant on air temperature. Studies have shown that these systems can reduce air temperature by 5–10°C at a height of 0.1 m from the surface [63].

Thermoelectric generators (TEGs) have shown promising results in reducing pavement surface temperatures. Studies indicate that these systems can achieve a surface temperature reduction of 4–14°C. The variability in temperature reduction is largely dependent on the specific design and implementation of the TEG system. Jiang et al. propose the use of a water tank to lower the temperature on the cold side of the thermoelectric generator. The results show an average temperature reduction of 5°C, up to a maximum of 9°C [64]. Further advancements in TEG design, such as those proposed by Elqattan et al., have shown greater temperature reductions, up to 14.1°C, by means of cooling elements like fans, heat sinks, and thermal paste [65].

In summary, energy harvesting pavements have an energy conversion efficiency of <15%, a dynamic modulus lower than that of traditional pavements, and poor adaptability to heavy loads; the construction cost and annual maintenance fee are high, and the economy is limited. Scale application needs to break through the

	Advantages	Disadvantages
Reflective pavement [66, 67]	Notable cooling effects: • A reduction in pavement temperature by 4.5–15°C and a decrease in air temperature in urban canyons by 0.5–3.5°C; • A reduction in urban energy consumption (approximately a 10–15% decrease in air-conditioning demand); • Suppression of the generation of pollutants such as ozone, and an extension of road service life.	Issues such as: • The deterioration of skid resistance may pose a threat to traffic safety; • There exists a contradiction between glare and thermal comfort; • Insufficient durability necessitates periodic maintenance and the cost is high.
Permeable pavement [34, 53–59, 68]	• Facilitate rainwater infiltration, reduce surface runoff, and mitigate urban flooding. • Enhance water quality by filtering pollutants and support urban greenery by providing space for tree roots to grow. • Promote evaporative cooling, reducing the urban heat island effect.	• Surface clogging makes maintenance strategies more complex or not yet well optimized. • There are not yet design and construction methodologies (not all regions or applications are suitable for permeable pavements). • There are not enough studies related to their structural capacity and general costs.
Energy harvesting pavement [69–72]	• High performance in terms of surface temperature reduction. • Coupling the ability of generate electricity and/or stock thermal energy with UHI mitigation. • Coexistence with ITS (Intelligent Transportation Systems) for power supply or existing buildings for heating needs.	• Benefit-cost ratio very high, especially for solar road and TEGs. • Lack of full-scale experiments. • Lack of studies regarding the maintenance and the integration of energy harvesting pavements in urban areas.

Table 2.
Advantages and disadvantages of cool pavements.

bottleneck of efficiency, strength, and cost, relying on multi-physical field optimization, lightweight materials, and full-cycle cost control.

3.4 Summary of cool pavements in the mitigation of urban heat island

The previous sections have outlined key findings from the literature on the use of reflective, permeable, and energy-harvesting pavements as strategies for mitigating the urban heat island effect. To conclude this section, **Table 2** provides a comparative summary of the main advantages and limitations associated with each pavement type.

4. Conclusions

This chapter highlighted the working principles and main key findings reported in scientific literature concerning reflective, permeable, and energy harvesting pavements as strategies to mitigate the UHI effect in urban areas. Each alternative offers distinct capacities for reducing both surface and air temperatures, with the following key observations:

- *Reflective pavements* are promising candidates for a simple, effective, and low-cost solution, offering a significant cooling effect ranging from 4.5°C to 15°C for the surface and from 0.5°C to 3.5°C for the air temperature.
- *Permeable pavements*, while slightly less effective in UHI mitigation (with surface temperature reductions of 1–5°C and approximately 1°C for air temperature), also facilitate rainwater infiltration, making them a suitable solution for areas prone to flooding.
- *Energy harvesting pavements* are emerging and promising technologies, combining UHI mitigation (up to 20°C of surface temperature reduction for the asphalt solar collector) with the ability to store thermal energy and/or generate electricity.

However, the literature also reveals several disagreements and challenges. While the cooling effects of reflective pavements are well-documented, their long-term performance and the potential negative effects, such as light radiance, remain debated. Permeable pavements, although effective in UHI mitigation, are often criticized for their reduced structural stability and susceptibility to clogging, leading to performance fluctuations. Energy-harvesting pavements, though promising, are still in early stages of development and face significant technical and cost barriers.

Looking ahead, the future development of cool pavements will likely focus on:

- the use of innovative materials like thermochromic coatings and phase change materials to enhance cool pavement performance;
- the optimization of design and maintenance, focusing on improving durability, cost-effectiveness, and maintenance strategies;
- the implementation of more large-scale cool pavements to better understand their long-term performance and city impacts on temperature reduction;
- the coexistence of cool pavements with other strategies like urban greening for more comprehensive UHI mitigation approaches and
- the development of supportive policies to promote their application.

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References

- [1] Forster PM, Smith CJ, Walsh T, Lamb WF, Lamboll R, Hauser M, et al. Indicators of Global Climate Change 2022: Annual update of large-scale indicators of the state of the climate system and human influence. *Earth System Science Data*. 2023;**15**(6): 2295-2327
- [2] World Meteorological Organization. Global Climate Predictions Show Temperatures Expected to Remain at or Near Record Levels in Coming 5 Years [Internet]. 2025. Available from: <https://wmo.int/news/media-centre/global-climate-predictions-show-temperatures-expected-remain-or-near-record-levels-coming-5-years>
- [3] Santamouris M. Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings*. 2020;**207**:109482
- [4] Martin-Vide J, Sarricolea P, Moreno-García MC. On the definition of urban heat island intensity: The “rural” reference. *Frontiers in Earth Science*. 2015;**3**:3-24. Available from: <https://www.frontiersin.org/journals/earth-science/articles/10.3389/feart.2015.00024/full>
- [5] Climate Central. Urban Heat Hot Spots [Internet]. Available from: <https://www.climatecentral.org/climate-matters/urban-heat-islands-2023>
- [6] Hardin AW, Liu Y, Cao G, Vanos JK. Urban heat island intensity and spatial variability by synoptic weather type in the northeast U.S. *Urban Climate*. 2018; **24**:747-762
- [7] Mohan M, Kikegawa Y, Gurjar BR, Bhati S, Kolli NR. Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. *Theoretical and Applied Climatology*. 2013;**112**(3): 647-658
- [8] Kolokotroni M, Giridharan R. Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy*. 2008;**82**(11):986-998
- [9] Ma YX, Yu AC. Impact of urban heat island on high-rise residential building cooling energy demand in Hong Kong. *Energy and Buildings*. 2024;**311**:114127
- [10] Wang W, Zhou W, Ng EYY, Xu Y. Urban heat islands in Hong Kong: Statistical modeling and trend detection. *Natural Hazards*. 2016;**83**(2):885-907
- [11] Benjamin Obe O, Morakinyo TE, Mills G. Assessing heat risk in a sub-saharan African humid city, Lagos, Nigeria, using numerical modelling and open-source geospatial socio-demographic datasets. *City and Environment Interactions*. 2023;**20**: 100128
- [12] Bassett R, Young PJ, Blair GS, Samreen F, Simm W. The Megacity Lagos and Three Decades of Urban Heat Island Growth. 2020. Available from: <https://journals.ametsoc.org/view/journals/apme/59/12/jamc-d-20-0059.1.xml>
- [13] Praticò F, Giunta M, Marino C, Attinà A. Pavement albedo and sustainability: An experimental investigation. In: 7th International Conference on Maintenance and Rehabilitation of Pavement and Technological Control MAIREPAV; Auckland, New Zealand. 2012

- [14] Dudorova NV, Belan BD. The energy model of urban heat Island. *Atmosphere*. 2022;**13**(3):457
- [15] Kolokotroni M, Ren X, Davies M, Mavrogianni A. London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings*. 2012;**47**:302-311
- [16] Abbassi Y, Ahmadikia H, Baniasadi E. Impact of wind speed on urban heat and pollution islands. *Urban Climate*. 2022;**44**:101200
- [17] Mohajerani A, Bakaric J, Jeffrey-Bailey T. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*. 2017;**197**:522-538
- [18] Roxon J, Ulm FJ, Pellenq RJM. Urban heat island impact on state residential energy cost and CO₂ emissions in the United States. *Urban Climate*. 2020;**31**: 100546
- [19] Gago EJ, Roldan J, Pacheco-Torres R, Ordóñez J. The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*. 2013;**25**: 749-758
- [20] Ong BL. Green plot ratio: An ecological measure for architecture and urban planning. *Landscape and Urban Planning*. 2003;**63**(4):197-211
- [21] Miao C, Yu S, Hu Y, Zhang H, He X, Chen W. Review of methods used to estimate the sky view factor in urban street canyons. *Building and Environment*. 2020;**168**:106497
- [22] Yupeng W, Dixuan M, Man L, Dian Z. Urban renovation and the simulation evaluation of urban climate change in residential and commercial districts: A case of Xi'an, China. In: *Sustainable Cities—Authenticity, Ambition and Dream*. IntechOpen; 2018. Available from: <https://www.intechopen.com/chapters/undefined/chapters/63651>
- [23] Ramírez AZ, Muñoz CB. Albedo effect and energy efficiency of cities. In: *Sustainable Development—Energy, Engineering and Technologies—Manufacturing and Environment*. IntechOpen; 2012. Available from: <https://www.intechopen.com/chapters/undefined/chapters/29929>
- [24] Hu H, Vizzari D, Zha X, Roberts R. Solar pavements: A critical review. *Renewable and Sustainable Energy Reviews*. 2021;**152**:111712
- [25] Cabral DO. Photovoltaic-thermal solar collectors—A rising solar technology for an urban sustainable development. In: *Urban Transition—Perspectives on Urban Systems and Environments*. IntechOpen; 2022. Available from: <https://www.intechopen.com/chapters/undefined/chapters/81467>
- [26] Snyder H. Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*. 2019;**104**:333-339
- [27] Chen J, Wang H, Xie P. Pavement temperature prediction: Theoretical models and critical affecting factors. *Applied Thermal Engineering*. 2019;**158**: 113755
- [28] Saliko D, Ahmed A, Erlingsson S. Development and validation of a pavement temperature profile prediction model in a mechanistic-empirical design framework. *Transportation Geotechnics*. 2023;**40**:100976
- [29] Motamedi Z, Bansal T, Mattsson H, Åström J, Casselgren J. A dynamic

boundary condition finite difference model for predicting pavement profile temperatures: Development and validation. *Transportation Engineering*. 2024;**18**:100287

[30] Qin Y, Hiller JE. Understanding pavement-surface energy balance and its implications on cool pavement development. *Energy and Buildings*. 2014;**85**:389-399

[31] Tan H, Kotamarthi R, Ray P. Estimation of surface sensible heat flux due to precipitation over CONUS and its impact on urban extreme precipitation modeling. *Journal of Hydrometeorology*. 2024;**25**(3):413-424

[32] Li H, Harvey J, Kendall A. Field measurement of albedo for different land cover materials and effects on thermal performance. *Building and Environment*. 2013;**59**:536-546

[33] Kotak Y, Gul MS, Muneer T, Ivanova SM. Investigating the impact of ground albedo on the performance of PV systems. *CIBSE Technical Symposium*. 2015;1-16

[34] Muttuvelu DV, Wyke S, Vollertsen J. Are permeable pavements a sustainable solution? A qualitative study of the usage of permeable pavements. *Sustainability*. 2022;**14**(19):12432

[35] Fondation Ferec—PRototype d'Evaluation sur Voirie de l'Infiltration et Ruissellement de l'Eau [Internet]. Available from: <https://fondation-ferec.fr/wp-content/uploads/PREVOIRE/38/>

[36] Kayhanian M, Li H, Harvey JT, Liang X. Application of permeable pavements in highways for stormwater runoff management and pollution prevention: California research experiences. *International Journal of Transportation*

Science and Technology. 2019;**8**(4): 358-372

[37] Saadeh S, Ralla A, Al-Zubi Y, Wu R, Harvey J. Application of fully permeable pavements as a sustainable approach for mitigation of stormwater runoff. *International Journal of Transportation Science and Technology*. 2019;**8**(4): 338-350

[38] Scholz M, Grabowiecki P. Review of permeable pavement systems. *Building and Environment*. 2007;**42**(11):3830-3836

[39] Abbas FA, Alhamdo MH. Thermal response of an asphalt solar collector: Numerical and experimental validation. *Case Studies in Thermal Engineering*. 2023;**52**:103656

[40] Hasebe M, Kamikawa Y, Meiarashi S. Thermoelectric generators using solar thermal energy in heated road pavement. In: *The 25th International Conference on Thermoelectrics*. Vienna, Austria; 2006. pp. 697-700. Available from: <https://ieeexplore.ieee.org/document/4133389>

[41] Wu G, Yu X. System Design to Harvest Thermal Energy Across Pavement Structure. Cleveland, USA: 2012 IEEE Energytech; 2012. pp. 1-4. Available from: <https://ieeexplore.ieee.org/document/6304703>

[42] Gong X, Liu Q, Lv Y, Chen S, Wu S, Ying H. A systematic review on the strategies of reducing asphalt pavement temperature. *Case Studies in Construction Materials*. 2023;**18**:e01852

[43] Seifeddine K, Amziane S, Toussaint E, Ouldboukhite SE. Review on thermal behavior of cool pavements. *Urban Climate*. 2023;**51**:101667

[44] You Z, Zhang M, Wang J, Pei W. A black near-infrared reflective coating

based on nano-technology. *Energy and Buildings*. 2019;**205**:109523

[45] Santamouris M, Synnefa A, Karlessi T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Solar Energy*. 2011;**85**(12): 3085-3102

[46] Hu J, Yu X(B). Innovative thermochromic asphalt coating: Characterisation and thermal performance. *Road Materials and Pavement Design*. 2016;**17**(1):187-202

[47] Qin Y. A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews*. 2015;**52**:445-459

[48] Santamouris M, Gaitani N, Spanou A, Saliari M, Giannopoulou K, Vasilakopoulou K, et al. Using cool paving materials to improve microclimate of urban areas—Design realization and results of the flisvos project. *Building and Environment*. 2012;**53**:128-136

[49] Mohegh A, Rosado P, Jin L, Millstein D, Levinson R, Ban-Weiss G. Modeling the climate impacts of deploying solar reflective cool pavements in California cities. *Journal of Geophysical Research-Atmospheres*. 2017;**122**(13): 6798-6817

[50] Carnielo E, Zinzi M. Optical and thermal characterisation of cool asphalts to mitigate urban temperatures and building cooling demand. *Building and Environment*. 2013;**60**:56-65

[51] Liu Q, Wu L, Wang Y, Tang N, Wang X, Gao L, et al. A novel functional coating with 2DMts/SA phase change material as filler and its pavement temperature regulation performance. *Materials Letters*. 2022;**306**:130905

[52] Rahman T, Suhendri, Tajudin AN, Suwanto F, Sudigdo P, Thom N. Durability evaluation of heat-reflective coatings for road surfaces: A systematic review. *Sustainable Cities and Society*. 2024;**112**:105625

[53] Liu Z, Tian Y, Ma B, Si W, Wang X. Numerical analysis of temperature reduction effect of permeable pavements. In Review. 2021:1-32. Available from: <https://www.researchsquare.com/article/rs-287873/v1>

[54] Butler A, Rowan T, Paschalis A. Investigation of Thermal Cooling Potential of Permeable Paving at an Urban Trial Site in London, UK 2023. Vienna, Austria: EGU General Assembly; 2023. p. EGU-14713. Available from: <https://ui.adsabs.harvard.edu/abs/2023EGUGA.2514713B>

[55] Evaluating the Role of Green Infrastructure in Microclimate and Building Energy Efficiency [Internet]. Vienna – Austria: EGU General Assembly; 2023. Available from: <https://www.mdpi.com/2075-5309/14/3/825>

[56] Ranieri V, Coropulis S, Berloco N, Fedele V, Intini P, Laricchia C, et al. The effect of different road pavement typologies on urban heat island: A case study. *Sustainable and Resilient Infrastructure*. 2022;**7**(6):803-822

[57] Haselbach L. Pervious Concrete and Mitigation of the Urban Heat Island Effect. 2009. Available from: <https://trid.trb.org/View/880515>

[58] Xie J, Zhou Z. Numerical analysis on the optimization of evaporative cooling performance for permeable pavements. *Sustainability*. 2022;**14**(9):4915

[59] Chen X, Wu C, Chen Z, Chen C, Jin C. Influence of meteorological factors on evaporative cooling of steel slag

- permeable concrete pavement. *International Journal of Pavement Engineering*. 2023;**24**(2):2115493
- [60] Xie P, Wang H. Potential benefit of photovoltaic pavement for mitigation of urban heat island effect. *Applied Thermal Engineering*. 2021;**191**:116883
- [61] Efthymiou C, Santamouris M, Kolokotsa D, Koras A. Development and testing of photovoltaic pavement for heat island mitigation. *Solar Energy*. 2016;**130**:148-160
- [62] Mallick R, Chen B, Bhowmick S, Hulen MS. Capturing Solar Energy from Asphalt Pavements. 2008. Available from: <https://www.semanticscholar.org/paper/Capturing-Solar-Energy-from-Asphalt-Pavements-Mallick-Chen/b3052cc952011a6dcd4196aac736ed88f22e3e94>
- [63] Nasir SD, Xu W, Vital B, Pantua C, Zhou B, Calautit J, et al. Urban road and pavement solar collector system for heat island mitigation: Assessing the beneficial impact on outdoor temperature. *IOP Conference Series: Earth and Environmental Science*. 2020; **463**(1):012038
- [64] Jiang W, Xiao J, Yuan D, Lu H, Xu S, Huang Y. Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions. *Energy and Buildings*. 2018;**169**:39-47
- [65] Elqattan AA, Elrayies GM. Developing a novel solar-driven cool pavement to improve the urban microclimate. *Sustainable Cities and Society*. 2021;**64**:102554
- [66] Zhu S, Mai X. A review of using reflective pavement materials as mitigation tactics to counter the effects of urban heat island. *Advanced Composites and Hybrid Materials*. 2019; **2**:381-388. DOI: 10.1007/s42114-019-00104-9
- [67] Huang X, Bou-Zeid E, Pigliautile I, Pisello AL, Mandal J. Optimizing retro-reflective surfaces to untrap radiation and cool cities. *Nature Cities*. 2024;**1**(4): 275-285. DOI: 10.1038/s44284-024-00047-3
- [68] Buyung NR, Ghani ANA. Permeable pavements and its contribution to cooling effect of surrounding temperature. *AIP Conference Proceedings*. 2017;**1892**(1):170003
- [69] Vizzari D, Bahrani N, Fulco G. Coexistence of energy harvesting roads and intelligent transportation systems (ITS). *Infrastructures*. 2023;**8**(1):14
- [70] Vizzari D, Dumoulin J, Chailleux E, Genesseeux E, Lavaud S, Bouron S, et al. Thermal behavior of a novel solar hybrid road for energy harvesting. *Journal of Testing and Evaluation*. 2023; **51**(4):2282-2295
- [71] Hu H, Zha X, Niu C, Wang Z, Lv R. Structural optimization and performance testing of concentrated photovoltaic panels for pavement. *Applied Energy*. 2024;**356**:122362
- [72] Vizzari D, Puntorieri P, Praticò F, Fiamma V, Barbaro G. Energy harvesting from solar and permeable pavements: A feasibility study. *Annales de Chimie Science des Matériaux*. 2018; **42**(4):502-520

Development of an Accelerated Pavement Testing System: Effect of Various Climatic Factors

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and Dawid D'Melo*

Abstract

An accelerated pavement testing (APT) system has been developed to evaluate the impact of climate factors—such as UV radiation, precipitation, thermal cycling, and pavement temperature—on pavement performance. This system is designed to support the development of new materials and pavement design strategies that are resilient to extreme climate events. A sensitivity analysis using the Long-Term Pavement Performance (LTPP) database confirmed that climate variables significantly influence pavement deterioration, reinforcing the need for a controlled testing environment like the APT system. A novel method was introduced to measure rutting depth in test sections using the APT system. Tests conducted on asphalt specimens made with unmodified bituminous binder revealed that rutting was more severe under simulated climate conditions than in conventional Hamburg Wheel Tracking Tests. This suggests that traditional methods may underestimate the damage caused by environmental factors. The APT system was also used to simulate extreme temperature events, specifically short-duration temperature overruns. Results showed that even brief exposures (10% of the total test cycle) to elevated temperatures significantly increased rutting compared to conventional testing outcomes. Preliminary evaluations further indicated that rutting is highly sensitive to both the surface temperature and the temperature gradient between the pavement surface and its centre.

Keywords: accelerated pavement testing (APT), climate resilience, rutting depth, temperature overrun, pavement performance

1. Introduction

There has been a significant impact of climate change globally, specifically with respect to the occurrence of extreme weather events across the globe, and also in terms of deviations observed in annually predicted climate conditions and actual climate conditions on a regular basis [1, 2].

This is indicated by the occurrence of extreme events on a more frequent basis globally. An example of this phenomenon is as described below.

1. In 2022, the UK experienced a summer where the average air temperature was in excess of 40°C. The winters in 2022 also experienced temperatures of at least 3°C lower than normal and an average temperature which has been the lowest since 2010 [3].
2. Similar events have been seen across Asia, North America, Canada and Europe as well.

The pavement design approaches are generally based on average pavement temperatures, rainfall, and thermal cycling rates. Hence, the impact of extreme deviations in these factors on pavement performance is not appropriately accounted for when average parameters are used. Since the frequency of such events is increasing at a global level, there is a lot of research that is being focused on developing techniques/pavement design guidelines that can account for such events. The design of roads accounts for various climate factors like precipitation levels, mean high and low temperatures, rapid variations in temperatures, and load factors like traffic frequency, traffic growth rates, type of vehicles [3]. If there are deviations in the assumed climate and load factors in the pavement design phase, then the pavement life and performance may not be as per the initial design [3]. Designing pavements to account for changes in climate conditions has been a key area of research in recent years [4, 5].

A few studies have reported that the occurrence of extreme events like increased precipitation and heat waves can result in increased roughness and increased rutting damage in pavement structures [6].

Several studies have evaluated the impact of extreme events like increased precipitation levels and heat waves using mechanical empiristic pavement design guidelines (MEPDG). The results have indicated that the damage rate on pavements increases due to these extreme events, and one of the possible ways to mitigate this is to utilize different binders for making a pavement. In addition, one of the other proposed ways is to improve the resilience of the various pavement layers primarily by increasing the pavement thickness or by improving the bonding between various pavement layers [7, 8].

One of the design options to account for sudden climate events is the perpetual pavement design approach [9]. Perpetual pavements are a multilayer construction where the surface course, binder course, base layer, and subbase layer are designed in such a way that the overall strain in the pavement is within the endurance limit, which then eliminates the failure of the pavement by the bottom-up fatigue cracking process. The surface layer in such a design provides resistance to rutting and top-down cracking, the base layer provides resistance to fatigue failure and bottom-up cracking, and sometimes the base layer is split into two different layers with different binder contents [9, 10].

In case of perpetual pavements, a top rut-resistant asphalt layer is constructed, and this surface course is periodically replaced based on the nature/design of the pavement. The perpetual pavement design approach requires the use of thicker base layers, and hence the upfront overall cost of making such pavements is higher than standard pavements with four layers (surface course, base course, subbase, and subgrade). The increased upfront cost of developing perpetual pavements is one of the key blockers in adopting this design practice [9]. This approach of perpetual pavement design is generally adopted for highways or roads that have significant economic

importance, where failure/frequent maintenance can result in significant economic loss, and in the overall cost-benefit analysis, it stacks up. Hence, most of the road infrastructure development would still proceed by the conventional pavement design approaches, which would then mean that other design approaches need to be adopted for thin pavement structures to account for climate change. The use of alternative binder materials is one of the possible ways to mitigate the effects of climate change. Another way of improving climate resilience is by adopting various pavement design practices. A few feasible options that have been evaluated in the past few years are discussed below.

One of the possible ways to account for climate factors is to develop materials that improve pavement durability. This approach involves the use of materials/pavement designs that can increase the service life of a pavement. The design-based methods involve perpetual pavement design, dynamic pavement design, viscoelastic pavement design methods, self-healing pavement structures, and pavement condition monitoring based approaches [11–14]. The other approach is to look at pavement materials which involves use of self-healing binders, composite binders (fiber modified, carbon nanotube/nanoparticle modified binders), use of alternative binders like epoxy based binders, binders with improved aging resistance and binders incorporating phase change materials [15–18]. One of the important aspects by either design based, or material-based approaches is to understand how these solutions perform with respect to changes in weather conditions by experimental methods.

In recent years there are limited number of studies that have focused on experimental evaluation of pavement structures using accelerated pavement testing systems (APTS). This chapter investigates the significance and impact of climate factors on pavement performance using an accelerated pavement testing system and also proposes the possible ways to incorporate impact of climate change on pavement performance.

2. Materials and methods

2.1 Materials

A penetration grade binder with the following properties (as shown in **Table 1**) is used in this study.

2.2 Methodology

The evaluation of the impact of climate factors on pavement performance is investigated as per **Figure 1**. The long-term pavement performance (LTPP) infopave

Penetration (dmm)	64
Softening point (°C)	48.6
Dynamic viscosity (cP) at 135°C)	230
Change in softening point (RTFOT)(°C)	4.6

Table 1.
Properties of penetration grade binder used in this study.

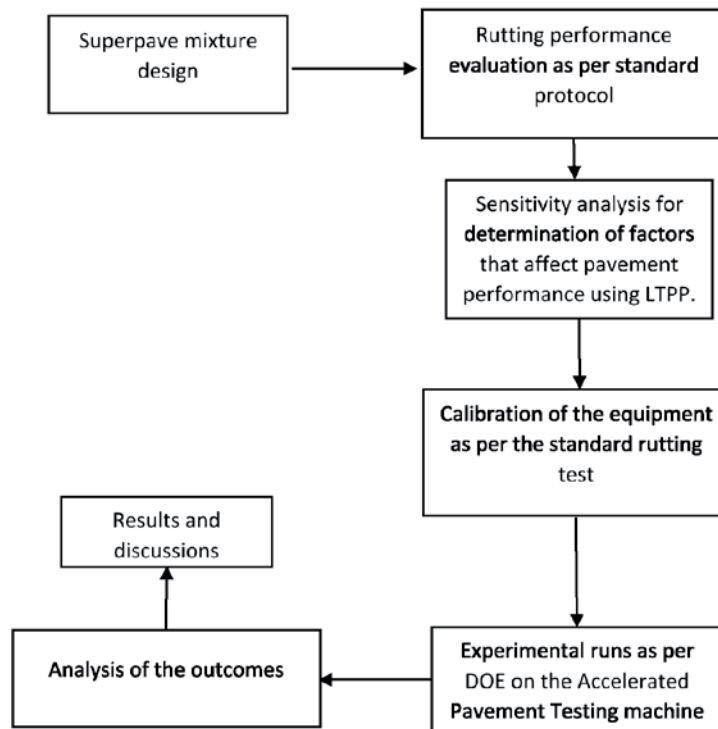


Figure 1.
The procedure adopted for developing pavement life factors.

pavement forecasting tool has been used in this study for performing a sensitivity analysis. Regression analysis has been done using MATLAB 2022R. The regression coefficients in the model equations indicate the significance of each of the factors on pavement performance.

2.3 Mixture design

The Superpave MS2-1 gradation and mixture design approach was used in this study, as shown in **Figure 2**. The information on the gradation of the aggregates is provided in **Table 2**. **Table 3** contains the details of the mixture design including the optimum binder content and the volumetrics required for the determination of the optimum binder content.

2.4 Rutting evaluation according to standard protocol

The commonly adopted test for evaluating the rutting performance of asphalt concrete mixture is the Hamburg Wheel-track test (HWTT) and the rutting susceptibility test using Asphalt Pavement Analyzer (APA) [19]. The average rutting results for the prepared asphalt specimens are mentioned in **Table 4**. There is no specific criteria reported in the standard for aggregate sizes above 19 mm nominal size in these standard tests. The binder used in this study is a PG64-22 unmodified short residue binder. Hence, the test temperature for the rutting test has been chosen to be 50 and 64C as per specifications.

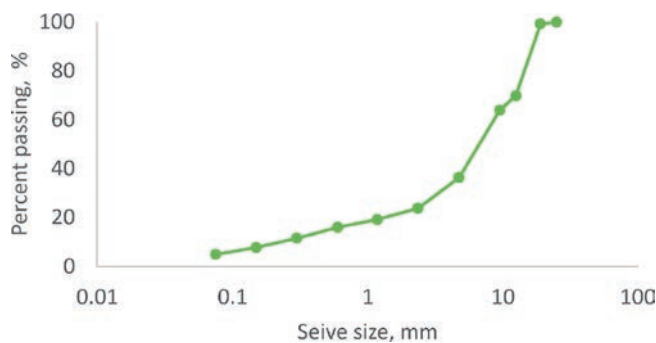


Figure 2.
 Gradation curve.

Sieves size SI (mm)	Gradation, percent Passing
25	100
19	99
12.5	70
9.5	64
4.75	36
2.36	24
1.18	19
0.6	16
0.3	11
0.15	8
0.075	5

Table 2.
 Gradation details.

Air voids (%)	4
Optimum binder content (w/w) (%)	4.2
Voids Filled with bitumen (%)	70
Voids in mineral aggregates (%)	13
Dust to binder ratio (%)	1.2

Table 3.
 Mixture design details.

2.5 Sensitivity analysis

The performance of an asphalt pavement is affected by several factors like applied load, loading time, design of a pavement, minimum and maximum pavement temperature, rain fall/snow fall levels, and thermal cycling rates and frequency. The impact of these factors is generally addressed by the design of the pavement and the selection of the materials used to make a pavement. Since all these factors affect the

Test	Specification	Test temperature	Rut depth (mm)
Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures	AASHTO T324-19	50°C	6
Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)	AASHTO T340-10	64°C	6.7

Table 4.
Results from rutting evaluation of asphalt specimens.

performance of a pavement, it is important to understand the sensitivity of pavement performance to these factors. A sensitivity analysis study would then indicate the most key factors that affect pavement performance, which can then be further used to develop experimental methods that can measure the impact of the identified factors on pavement performance.

2.6 Approach for sensitivity analysis evaluations using LTPP

The American Association of State Highway and Transportation Officials (AASHTO), under the long-term pavement performance program (LTPP), has field data for pavement performance for more than 800 pavement test sections. These test sections have been cored periodically, and the cores have been tested for mechanical properties, which further have been used to fine-tune various pavement performance models, that is, rutting, fatigue, and thermal cracking models. In addition, actual performance data with regard to failure have been recorded for these test sections. LTPP has developed a pavement forecasting tool based on this information, which has been used to do a sensitivity analysis. A design scenario in which surface course overlays have been done on existing pavements has been evaluated in this study.

A L9 orthogonal design [20] with six input parameters and five levels has been used for sensitivity assessment, resulting in a total of 25 runs. The response variables used in this study were rutting, fatigue, and surface roughness. The design used as per the L9 orthogonal design is shown in **Table 5**.

The range of parameters used in this study was defined as per the observed maximum and minimum for each of the input variables in the LTPP database. The response variables for the above experimental design are shown in **Table 6** below.

Traffic (X1)	Annual cooling index (X2)	Annual freezing index (X3)	Annual precipitation(X4)	Annual freeze-thaw cycles (X5)	Structural number (X6)
100,000	480	360	320	38	3
300,000	960	720	640	76	5
500,000	1440	1080	960	114	7
700,000	1920	1440	1280	152	9
1,000,000	2400	1800	1600	190	11
X1	X2	X3	X4	X5	X6
100000'	480	360	320	38	3
100,000	960	720	640	76	5

Traffic (X1)	Annual cooling index (X2)	Annual freezing index (X3)	Annual precipitation(X4)	Annual freeze-thaw cycles (X5)	Structural number (X6)
100,000	1440	1080	960	114	7
100,000	1920	1440	1280	152	9
100,000	2400	1800	1600	190	11
300,000	480	720	960	152	11
300,000	960	1080	1280	190	3
300,000	1440	1440	1600	38	5
300,000	1920	1800	320	76	7
300,000	2400	360	640	114	9
500,000	480	1080	1600	76	9
500,000	960	1440	320	114	11
500,000	1440	1800	640	152	3
500,000	1920	360	960	190	5
500,000	2400	720	1280	38	7
700,000	480	1440	640	190	7
700,000	960	1800	960	38	9
700,000	1440	360	1280	76	11
700,000	1920	720	1600	114	3
700,000	2400	1080	320	152	5
1,000,000	480	1800	1280	114	5
1,000,000	960	360	1600	152	7
1,000,000	1440	720	320	190	9
1,000,000	1920	1080	640	38	11
1,000,000	2400	1440	960	76	3

Table 5.
Test matrix using the L9 orthogonal design.

Rutting (m/km) (10)	Fatigue (10) (% wheel path)	IRI m/km (10)	Rutting (m/km) (20)	Fatigue (% wheel path) (20)	IRI m/km (20)	Rutting (m/km) (30)	Fatigue (30% wheel path)	IRI m/km (30)
5.09	27.8	1.8	6.23	51.04	2.35	7.02	71.78	3.05
5.72	9.97	1.8	6.92	19.76	2.46	7.74	28.84	3.35
6.988	0.015	1.8	8.164	4.552	2.53	8.942	8.72	3.55
9.16	0	1.8	10.26	0	2.63	10.97	0	3.73
12.899	6.332	1.8	13.808	7.22	2.66	14.37	8.11	3.913
7.91	3.97	1.8	10.33	12.71	2.46	12.07	21.02	2.97

Rutting (m/km) (10)	Fatigue (10) (%) wheel path)	IRI m/km (10)	Rutting (m/km) (20)	Fatigue (% wheel path) (20)	IRI m/km (20)	Rutting (m/km) (30)	Fatigue (30% wheel path)	IRI m/km (30)
10.48	0	1.8	12.02	3.55	2.37	13.027	7.65	3.11
7.16	0	1.8	8.15	10.39	2.54	8.799	24.56	3.37
4.257	6.263	1.8	4.694	7.675	2.68	4.971	9.026	3.997
6.81	0	1.8	7.33	1.77	2.47	7.65	3.36	3.41
7.51	10.17	1.8	9.7	37.62	2.49	11.26	66.55	3.44
5.17	2.51	1.8	6.39	6.3	2.62	7.23	9.58	3.8
6.86	4.51	1.8	7.43	6.07	2.53	7.78	7.58	3.52
9.36	0	1.8	10.24	1.18	2.38	10.79	2.7	2.82
5.83	0	1.8	6.18	3.65	2.52	6.39	9.06	3.47
7.85	0.82	1.8	9.98	4.47	2.54	11.48	7.68	3.58
5.26	7.18	1.8	6.43	19.39	2.66	7.23	31.07	3.34
6.37	4.2	1.8	7.58	15.09	2.44	8.39	25.996	3.31
8.46	0	1.8	8.8	1.65	2.34	9.001	6.77	3.04
6.57	0	1.8	6.79	0	2.53	6.92	0	3.55
8.33	1.76	1.8	10.33	12.99	2.56	11.71	24.25	3.61
8.71	1.63	1.8	10.65	11.17	2.37	11.99	21.34	3.11
7.91	0.24	1.8	9.29	1.73	2.49	10.22	2.93	3.45
4.78	2.76	1.8	5.38	7.57	2.59	5.77	11.92	3.72
6.36	2.46	1.8	6.24	4.69	2.49	6.17	6.85	3.03

Table 6.
Response variables for the various Input parameters.

The response variables for each of the scenarios are determined at three different time points or design life. This was done to assess if the sensitivity of the response variables changes with pavement life, since the design of the pavement changes with pavement life wherein pavements designed for a longer life would potentially be thicker and would also have a higher binder content.

2.7 Development of an accelerated pavement testing machine

Sample preparation: The dimension of the sample tested on the accelerated pavement testing machine is 380 mm long, 150 mm wide, and 50 mm thick. The air voids for the samples tested were in the range of $7 \pm 1\%$.

Equipment details: The equipment consists of four trains, which can accommodate three samples on each train, so that 12 samples can be tested at a time in one run. A representative image of the equipment is shown in **Figure 3**.

The equipment has been provided with a solar simulator lamp, which can provide a total of 2400 W of energy per sample/specimen. The power details of the lamp are provided in **Table 7** below. UV exposure on the sample in a period of 6 hours is equivalent to the UV exposure on the sample tested as per the ASTM D4798 in a



Figure 3.
 Accelerated pavement testing machine.

Description	IR/Visible (W)	UVA (W)	UVB (W)	Total (W)	Total UV exposure per sample (W)	Total IR exposure per sample (W)
Osram Vitalux Ultra	283.4	13.6	3	300	132.8	2267.2
Total UV energy incident on the sample in 6 hours (Joules)					2.87E+06	
Total UV energy incident on the sample in 90-days as per ASTM D4798 weathering technique (Joules)					2.31E+06	

Table 7.
 Incident UV radiation on the asphalt specimen as compared to ASTM D4798.

period of 90 days. It is well known in the literature that UV light acts as an accelerating factor in oxidation of asphalt and the rate of oxidation is directly proportional to the UV energy flux and also to temperature, hence a shorter time of UV exposure at an increased intensity can simulate the behavior of the binder over a longer time duration but at a lower UV intensity.

Each testing line is also provided with two air heaters of 2000 W, which can supply hot air at up to a upper temperature of 80°C. Each train is provided with a water sprinkler system for cooling the specimens and also a separate water recirculation system, as shown in **Figure 4**. The load application on the specimens uses a hydraulically controlled mechanism applied through arc-type geometry. Specimens are placed on a tray that is capable of moving at desired speeds to simulate the movement of a wheel on asphalt specimens.

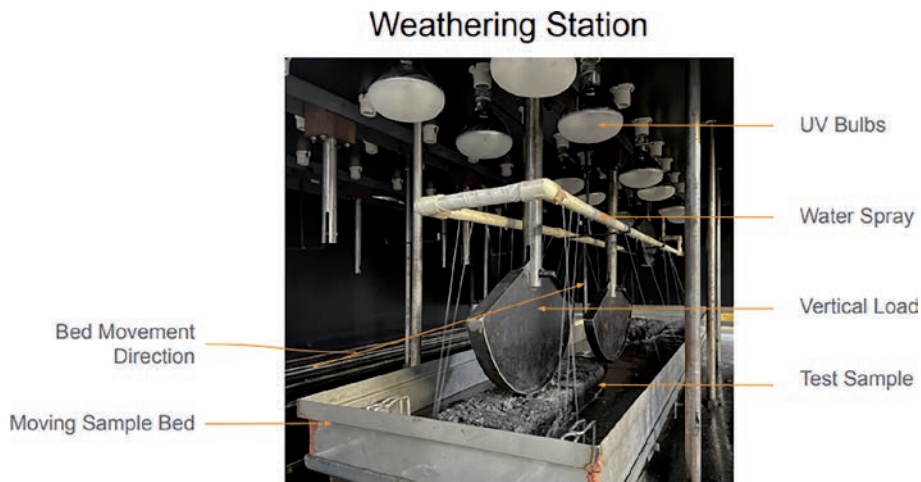


Figure 4.
Internal configuration of the accelerated pavement testing machine.

Test setup: The apparatus is fabricated such that the bottom trays move at a required frequency and the wheels are static. The test frequency can be varied between 0.3 and 1 Hz. The load that can be applied is in the range of 100–300 lbs.

The rutting depth in the specimen is measured using a laser-based system, where the laser is focused on a reference plate connected to the load application arc. The vertical movement of the reference plate is then tracked to quantify the rut depth.

3. Results and discussions

The first section for results covers the sensitivity analysis outcomes using the results from the LTPP estimates. A linear dependency of the response variables on the input parameters was assumed, and a coefficient correlation matrix was used to determine the primary dependency of the response variable on the input parameters, as shown in **Table 8**. **Table 8** indicates that pavement failure by all three mechanisms (rutting, fatigue, and IRI) is highly dependent on climate factors, as indicated by a high correlation with the climate factors. A similar outcome has been reported in some of the other studies as well, where the climate factors had a significant impact on pavement performance [8, 14].

The chosen response variables or pavement performance parameters are the most commonly observed reasons for pavement failure in case of overlay-type constructions.

3.1 Outcomes from regression analysis using the LTPP results

Regression analysis was done with the results generated to assess the sensitivity of the response variables to the input parameters. A standard square fitting technique was used in the regression estimates. The outcomes from the regression analysis have been reported *via* the surface plots as shown in **Figures 5-7**. The surface plots have been done for the three response variables as mentioned in the experimental section.

	Traffic	Annual cooling index	Annual freezing indices	Annual precipitation	Annual freeze thaw cycles	Structural number	Rutting (m/km) (20)	Fatigue (%wheel path) (20)	IRI m/km (20)	Rutting (m/km) (30)	Fatigue (30) (%wheel path)	IRI m/km (30)
Traffic	1											
Annual cooling index	0	1										
Annual freezing indices	0	0	1									
Annual precipitation	0	0	0	1								
Annual freeze thaw cycles	0	0	0	0	1							
Structural number	0	0	0	0	0	1						
Rutting(m/km) (20)	−0.12	−0.20	0.01	0.58	0.73	0.08	1.00					
Fatigue (%wheel path) (20)	−0.20	−0.60	−0.16	0.00	−0.49	−0.05	−0.14	1.00				
IRI m/km (20)	−0.08	0.20	0.79	−0.18	−0.14	0.48	−0.19	−0.21	1.00			
Rutting (m/km) (30)	−0.10	−0.34	0.00	0.55	0.70	0.13	0.99	−0.05	−0.19	1.00		
Fatigue (30) (%wheel path)	−0.15	−0.63	−0.17	0.12	−0.52	−0.04	−0.10	0.98	−0.23	0.00	1.00	
IRI m/km (30)	−0.12	0.19	0.62	−0.22	−0.04	0.44	−0.14	−0.19	0.85	−0.15	−0.23	1

Table 8.
 Correlation coefficients for the response variables on input parameters.

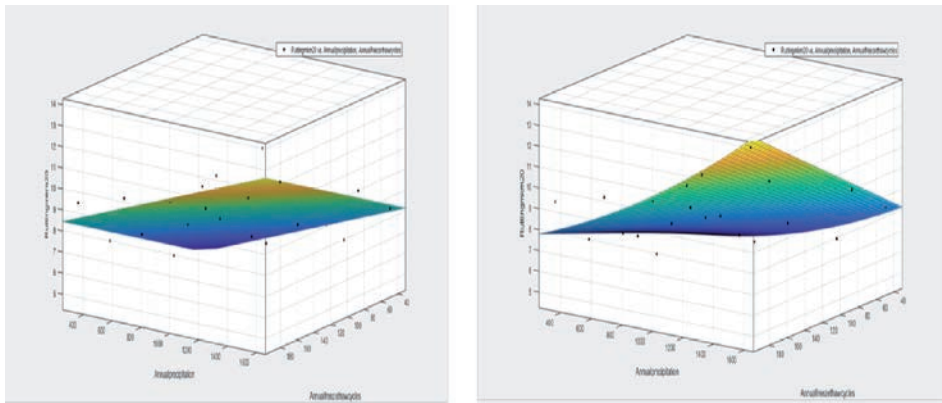


Figure 5.
Surface plots for rutting correlation with weather factors.

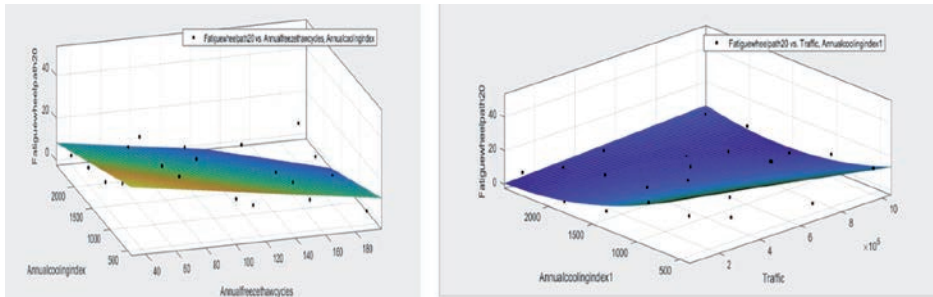


Figure 6.
Surface plots for fatigue correlation with weather factors.

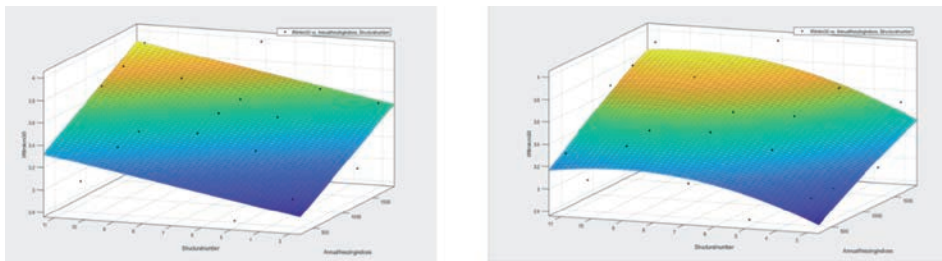


Figure 7.
Surface plots for IRI correlation with weather factors and structural number.

It can be seen from the surface plots that the rutting and fatigue behavior for overlay-type constructions are highly correlated to the climate factors, wherein more than 85% of the observed rutting and fatigue failures can be correlated to climate factors. Rutting-based pavement failure is more sensitive to annual precipitation as compared to annual freeze-thaw cycles, whereas fatigue-based failure is more sensitive to annual freeze-thaw cycles as compared to the annual cooling index. These results can be confirmed numerically as well as on the basis of the observed regression coefficients.

In case of pavement failure caused by increased surface roughness as measured by IRI, it was observed that the structural number of the pavement and annual freezing index can explain more than 85% of the reported results. In case of IRI-based failure, the increase in surface roughness is more sensitive to changes in annual freezing indices as compared to structural number. The presence of water or moisture induced rutting-based failure is already considered to be one of the accelerating factors for rutting-type damage, which is supported by the sensitivity analysis outcomes, and similar is the case for fatigue failure where in the accumulation of thermal stresses in asphalt layers due to freeze-thaw cycles is already considered to be an accelerating factor. In case of texture, a high correlation to the annual cooling index could be explained by a reduced bonding strength between the bitumen and the aggregates at very low temperatures. In addition, the brittleness of bitumen-based materials at lower temperatures could also result in the loss of texture. The regression and sensitivity analysis outcomes indicated that the weather factors affect pavement performance [5, 6, 8]. These results then indicate the requirement for experimental validation.

3.2 Development of an accelerated pavement testing machine

The accelerated pavement testing machine is different in design compared to the conventional rutting measurement systems. Hence, a test run was performed using the machine as per AASHTO T340-10 to assess if the developed testing system provides rutting results that are similar to conventional rutting measurements. Similar to the approach used for conventional rutting testing, the test specimens were conditioned for a period of 6 hours inside an oven. The heat transfer in this case was from all three sides of the test specimen.

There are several reports in the literature that have highlighted that pavements are like perpetual heat sinks, and under steady-state conditions, there is a temperature differential across the pavement surface. The temperature differential across the surface course of a pavement can go up to 15°C [21–26]. This being the case, a heat transport simulation in two dimensions was performed to assess the heating and the cooling cycle times. The simulation outcomes were also verified with experimental measurements, wherein the temperature differential between the surface and the center of the test specimen was measured. The heat transport simulation was performed using MATLAB 2024R. The following boundary conditions were used [22]:

Incident heat flux on each specimen: 2.26 kW
Density of the Asphalt specimen: 2.41 kg/m³
Thermal conductivity: 2.24 W/m°K
Heat capacity of the asphalt specimen: 963 J/Kg K
Absorptivity of the specimen at the surface: 0.85

Since the air temperature is fixed at 25°C, there is no heat transfer from air heating. The air supply in this case was not provided during the heating step of the specimen. Once the specimen reaches the desired surface temperature, the air supply is switched on at 25°C, with the primary aim of simulating the air oxidation effects in a pavement. Similarly, emissive losses have been set to zero since all internal surfaces of the equipment are fully reflective (polished metal surface).

The simulation results indicate that after 51 minutes of heating, the surface temperature can reach 64°C, and a temperature differential of 8°C between the top and the center of the sample can be achieved, as shown in **Figure 8**.

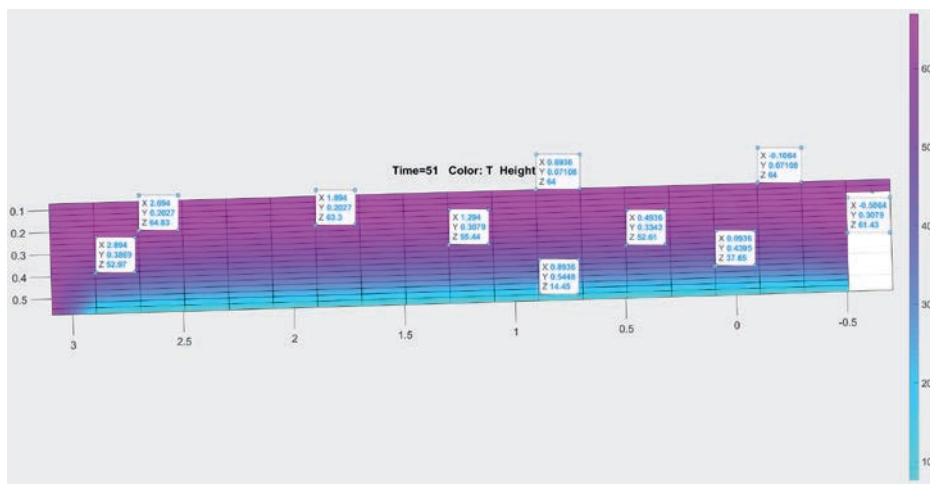


Figure 8.
Temperature profile inside the sample after 51 minutes of heating.

The simulation results indicated the following:

1. The roofing test procedure (cycle A) as prescribed in ASTM D4798 can be applied, where 51 minutes of heating followed by 9 minutes of cooling is used.
2. The simulation results also indicate that a higher/lower temperature differential can be achieved by changing the time of exposure or the incident flux intensity on the specimen.
3. A ON-OFF proportional control system linked to the temperature of the specimen on the surface could be applied. The temperature at the center will automatically be controlled based on the surface temperature.
4. The temperature of the specimen can go beyond 64°C since the sample has a high heat capacity and low thermal diffusivity, resulting in local temperature rise beyond 64°C [27].

The simulation results indicated that it is important to measure the temperature at the center of the specimen; hence, a sacrificial specimen with a thermocouple measuring the temperature at the center and the surface of the specimen was placed in the testing chamber. It was also observed in the simulation results that the temperature in the specimen is at 64°C within the first 10 mm below the surface. A 6-hour rutting test with application of load was done on the specimen, where the temperature of the surface was maintained at 64°C with an ON-OFF control mechanism for temperature control in the absence of water.

The results indicated (**Table 9**) that an average rut depth of 6 mm was seen with a standard deviation of 2 mm. This result was validated by testing six specimens under the same test conditions. These results were of a similar order when compared to the conventional method as reported in **Table 4**.

The next step was to set up a method that could assess the rutting tendency of asphalt specimens when subjected to weather conditions like UV exposure, thermal cycling, and water exposure. The baseline test condition chosen to perform this test

	Specimen 1	Specimen 2	Specimen 3	Average	Std deviation
Rut depth (mm)	4	6	8	6	2
Rut depth (mm)	3.8	6.2	7.8	5.9	2.0

Table 9.
Dry rut test outcomes of the accelerated pavement testing system.

Description	Value (mm)
Line 2.1 (measured max rut depth) mm	8.1
Line 2.2 (measured max rut depth) mm	10.8
Line 2.3 (measured max rut depth) mm	11.9
Line 3.1 (measured max rut depth) mm	8.2
Line 3.2 (measured max rut depth) mm	10.6
Line 3.3 (measured max rut depth) mm	12.2
Line 4.1 (measured max rut depth) mm	12.5
Line 4.1 (measured max rut depth) mm	8.2
Line 4.3 (measured max rut depth) mm	10.8
Line 1.1 (measured max rut depth) mm	8.1
Line 1.2 (measured max rut depth) mm	10.6
Line 1.3 (measured max rut depth) mm	9.2
Mean	10.10
Standard deviation	1.61
Standard error	0.5
95% Confidence bound (upper)	11.0
95% Confidence bound (lower)	9.8

Table 10.
Accuracy of the APTS in measuring rut depth.

was fixed to the time intervals used in the ASTM D4798 specification for testing roofing grade bituminous materials. This involves a 51-minute heating step followed by a 9-minute cooling step. The total testing time was initially set to a testing duration of 6 hours, which is in line with AASHTO T340-10.

The lamps used in this study simulated the solar spectrum, and each lamp has a rating of 300 W. There is no lateral loss due to irradiation from the lamp, and the lamp only covers an active area equivalent to its external diameter. A comparison of the energy supplied to the specimen was made as shown in **Table 10** below. It can be seen from **Table 7** that the UV energy supplied to the specimen in 90 days can be supplied in 6 hours by using these lamps. Since the oxidation of the binder has a first-order dependency on the UV energy supplied, the impact of UV flux on 90 days of exposure can be simulated by supplying the same amount of energy in a shorter duration.

A full load run on the APTS, as per the cycle mentioned below, was done

1. Heating cycle of 51 minutes with surface temperature maintained at 64°C (+/–) 1 °C.
2. Cooling cycle with water spray of 9 minutes. The speed of water supply was fixed at 10 cm/min.

3. Repeat the cycle for six cycles for a total duration of 6 hours (in line with the existing Hamburg test).
4. The cycle starts on the preheated sample, where the temperature of the surface of the sample reaches 64°C.

3.3 Accuracy of the APTS under full load

The sensitivity analysis results indicated that all three failure mechanisms (rutting, IRI, and fatigue) can occur in a surface course specimen. The current method development work considers rutting-type failure; in the future, texture measurement and fatigue measurement capabilities will also be developed in the APTS. It was very important to establish the accuracy of the rut depth measurement on the APTS under full load. Hence, a rut depth measurement at full load was performed on an asphalt specimen with the same binder, volumetrics, and gradation, using materials discussed in the experimental section. The result from this evaluation is reported in **Table 9**.

The standard deviation results indicate that the difference between the lowest and the highest value measured for a similar specimen is 3.2 mm at a 95% confidence level, and the uncertainty across the mean is 1.2 mm at a 95% confidence level. The range should be further reduced once a pooled standard deviation is estimated across multiple samples or by increasing the number of samples. But as per the current measurements, a factor of 3.2 mm is used to assess if two measured rut depths are similar or different.

3.4 Assessment of the impact of weather factors on rut depth

A DOE to assess the impact of various parameters on the rut depth in an asphalt specimen. A L9 orthogonal DOE was used to assess the impact of weather factors. There are four factors and three levels of variation, resulting in nine experimental runs, assuming no cross interaction, as shown in **Table 11**. Separate experimental runs will be done to assess the potential of cross-interaction between the input parameters.

	Load (lbs)	Frequency (Hz)	Center-to-surface temp differential (°C)	Surface temp of sample (°C)	Rut depth (mm)
1	158	1	8	64	9.1
2	158	0.75	12	70	10.0
3	158	0.5	4	40	2.9
4	100	1	12	40	1.6
5	100	0.75	4	64	4.3
6	100	0.5	8	70	4.4
7	200	1	4	70	9.3
8	200	0.75	8	40	4.2
9	200	0.5	12	64	13.4

Table 11.
Rut depth outcomes from the DOE runs.

The response variable in this case is rut depth. A correlation coefficient matrix was used to screen the variables that affect rut depth, as shown in **Table 12**. It can be seen from **Table 12** that rut depth has a poor correlation to frequency in the tested frequency range. Although frequencies lower than 0.5 Hz were not investigated, a potentially lower frequency would not significantly change the rutting behavior, since with a reduction in frequency, the mechanism of failure would move toward a strain-based or a fatigue-type failure. If the frequency of loading is higher, then the above correlation will hold since the loading time is lower. A regression analysis was performed on the results to assess the sensitivity of the parameters and measure rut depth. A two-parameter linear regression model has been used to assess sensitivity as shown by the surface plot in **Figures 9** and **10**. The two models reported in **Table 13** are the best-fit models that can be achieved based on the R^2 value. The coefficients of the models indicate that although the applied load has a very high correlation to the observed rut depth, the rut depth is more sensitive to the surface temperature and the surface-to-center temperature differential. These results are in line with the outcomes seen in Section 3.1.

	Load (lbs)	Frequency (Hz)	Center-to-surface temp differential (°C)	Surface temp of sample (°C)	Rut depth (mm)
Load (lbs)	1				
Frequency (Hz)	0	1			
Center-to-surface temp differential (°C)	0	0	1		
Surface temp of sample (°C)	0.00	0.00	0.00	1.00	
Rut depth (mm)	0.61	−0.03	0.31	0.66	1.00

Table 12.
Correlation coefficient matrix for the DOE runs.

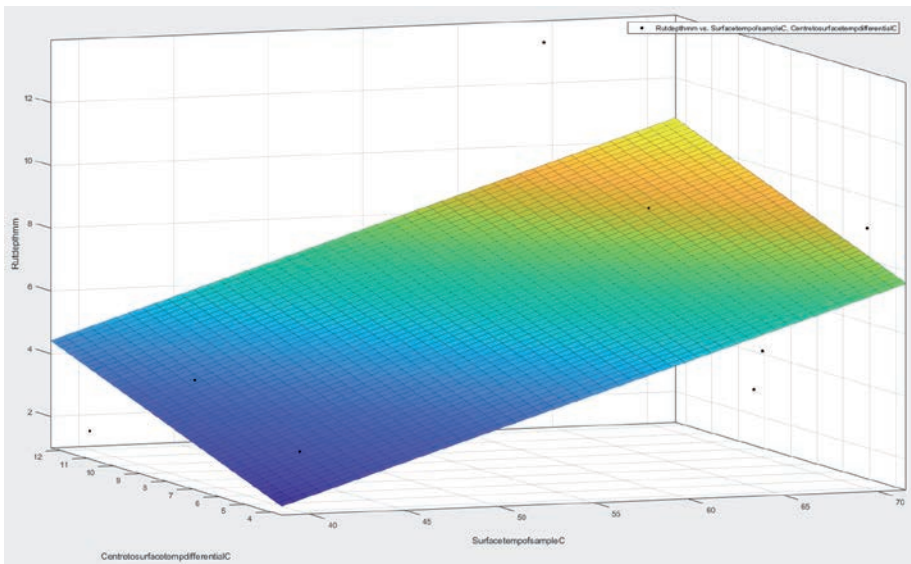


Figure 9.
Linear regression surface plots for rut depth with surface temperature and centre to surface differential as parameters.

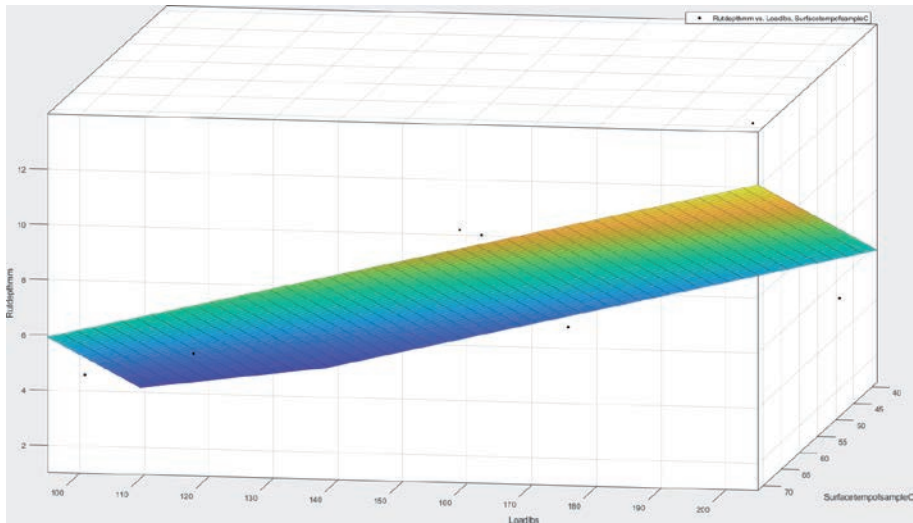


Figure 10.
Linear regression surface plots for rut depth with load and surface temperature as parameters.

Description	Comments
$a + b \cdot x + c \cdot y$	Functional form of the equation
0.54	R2 value
0.19	Coefficient for sample surface temperature
0.35	Coefficient for center-to-surface temperature differential
-7.3	Constant
0.81	R2 value
0.05	Coefficient for load
0.19	Coefficient for surface temperature
-13.5	Constant

Table 13.
Regression analysis outcomes for rut depth measurement results.

3.5 Effect of extreme event scenarios

Since in Section 3.4, it was seen that the surface temperature and the center-to-surface temperature differential play an important part in controlling the rut depths observed in an asphalt specimen, an experimental measurement was done to assess the effect of extreme events, where in extreme events are defined as scenarios where the surface temperature of the sample exceed by a marginal amount for a marginal time duration as compared to the total testing time. It is assumed that in a typical summer, there would be 10% of the days when the temperatures are higher than expected by 6°C. The total testing time in the accelerated pavement testing machine is 6 hours; hence, an extreme event occurrence where the surface temperature of the specimen exceeds the set temperature by 6°C for 30 minutes was assessed. The extreme event was placed at the start and the end of the cycle since the degree of impact would depend on the level of rutting already existing in the sample. A

	Load (lbs)	Frequency (Hz)	Center-to- surface temp differential (°C)	Surface temp of sample (°C)	Center temp	Rut depth (mm)	Comments
1	158	1	8	64	56	9.1	No extreme event
2	158	1	8	64	56	13.3	Extreme event at the end of the test cycle
3	158	1	8	64	56	17.5	Extreme event at the beginning of the test cycle

Table 14.
Impact of extreme events on rut depth.

frequency of 1 Hz and 158lbs was used, and a center-to-surface temperature differential of 8°C was applied. The result of this measurement is reported in **Table 14** below. The results indicate that extreme events, specifically an increase in the surface temperature of the specimen beyond the expected level, can result in a significantly higher rut depth in both scenarios. The impact of an extreme temperature event was observed at the beginning of the test run rather than at the end of the test run. The probable reason for this could be potentially explained by the proposition that when an extreme event happens at the beginning of a rutting test then as per the conventional rutting failure mechanism, the initial rutting rate is high, followed by a zone where the rate of rutting reduces due to internal compaction in the rutting section. The internal compaction increases the stiffness of the material, resulting in a higher resistance to any further rutting. Hence, the occurrence of an extreme event at the start has a higher damage potential than at the end.

4. Conclusions and future work

An accelerated testing procedure that accounts for the effects of temperature, UV exposure, load, and frequency has been proposed for testing of surface courses for rutting-based failures. The method has also been used to analyze the effect of extreme events, primarily heat waves. The preliminary results have indicated that rutting-based failures in pavement are sensitive to the center-to-surface temperature differential. In addition, the surface temperature of the pavement also has a significant impact on the observed rutting depth. The rutting depth observed compared to the conventional Hamburg wheel tracking test is higher when evaluated using the accelerated pavement testing machine. The increased degree of rutting could be attributed to climate factors like UV exposure, surface temperature, precipitation, and center-to-surface temperature differential, since the load and frequency are the same as used in the conventional Hamburg wheel tracking test. In the results presented, it can be seen that the rut depth in a pavement is high above a center-to-surface temperature differential of 8C. In real-life scenarios, this differential can go up to 20C. It was also observed that when the surface temperature is equal to the rutting temperature, there is a higher probability of a higher rut depth over multiple cycles.

In addition, it was also observed that the amount of rutting is higher when there are extreme events like temperature overrun for a short period (10% of the total time) in the overall testing cycle. A temperature overrun was applied for 30 minutes for a 300-minute test.

The future work will involve developing methods to determine the fatigue life and surface texture/roughness of a specimen using the accelerated pavement testing machine, where samples are exposed to various climatic factors. A performance-based mixture design procedure will also be developed wherein the performance of a pavement will be evaluated using this device, so that the impact of climate factors can be incorporated either by changing the type/content of binder or by changing mixture designs. The plan is also to assess various new binder materials that can improve the resilience of pavements to extreme events like heat waves, cold waves, and increased precipitation. An attempt to develop an empirical pavement performance model (rutting and fatigue) that accounts for extreme events will also be done.

Conflict of interest

None.

Notes/thanks/other declarations

None.

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References

- [1] Douglas E et al. Progress and challenges in incorporating climate change information into transportation research and design. *Journal of Infrastructure systems*. 2017;**23**
- [2] Matini N, Gulzar S, Underwood S, Castorena C. Evaluation of structural performance of pavements under extreme events: Flooding and heatwave case studies. *Transportation Research Record*. 2022;**2676**(7):233-248. DOI: 10.1177/03611981221077984
- [3] Tarefder RA, Zaman M, Hobson K. A laboratory and statistical evaluation of factors affecting rutting. *International Journal of Pavement Engineering*. 2003;**4**(1):59-68. DOI: 10.1080/10298430310001593263
- [4] Christoph S, Vidale P, Luthi D, Frei C, Haberli C, Linger M, et al. The role of increasing temperature variability in European summer heatwaves. *Nature*. 2004
- [5] Met Office: A review of the UK's climate in 2022 - Carbon Brief
- [6] Haslett K, Knott J, Stoner A, Sias J, Dave E, Jacobs J. Climate change impacts on flexible pavement design and rehabilitation practices. *Road Materials and Pavement Design*. 2021
- [7] Walubitu L, Arguelles G, Mendoza R, Lee Fuentes L. Comparative environmental assessment of rigid, flexible, and perpetual pavements: A case study of Texas. *Sustainability*. 2022
- [8] Cheneviere P, Ramdas V. Cost benefit analysis aspects related to long life pavements. *International Journal of Pavement Engineering*. 2007
- [9] Qiao Y, Dawson A, Parry T, Flintsch G, Wang W. Flexible Pavements and Climate Change: A Comprehensive Review and Implications, *Sustainability*. 2020
- [10] Yoder EJ, Witczk MW. Principles of Pavement Design. 2nd ed. John Wiley and Sons; 1991
- [11] Ridder NN, Ukola AM, Pitman AJ. Increased occurrence of high impact compound events under climate change. *NPJ Climate and Atmospheric Science*. 2022
- [12] Lu D, Tighe S, Xie W. Impact of flood hazard on pavement performance. *International Journal of Pavement Engineering*. 2018
- [13] Underwood B, Baek C, Kim Y. Simplified viscoelastic continuum damage model as platform for asphalt concrete fatigue analysis TRR. *Journal of Transportation Research Board*. 2004
- [14] Yu X, S.M. M, Yan J, Yin H. Morphological, thermal, and mechanical properties of asphalt binders modified by graphene and carbon nanotube. *Journal of Materials in Civil Engineering*. 2022
- [15] Setiawan D. The role of temperature differential and subgrade quality on stress, curling, and deflection behavior of rigid pavement. *Journal of Mechanical Behavior of Materials*. 2020
- [16] Erlingsson S, Ahmed A, Saliko D. Development and validation of a pavement temperature profile prediction model in a mechanistic-empirical design framework. *Transportation Geotechnics*. 2023
- [17] Graziano A, Marchetta V, Cadfisco S. Structural health monitoring of asphalt

- pavements using smart sensor networks: A comprehensive review. *Journal of Traffic and Transportation Engineering*. 2020
- [18] Abtahi S, Sheikhzadeh M, Hejazi S. Fiber-reinforced asphalt-concrete – A review. *Construction and Building Materials*. 2010
- [19] Qiu J, Van De Ven M, Yu W, Molenaar A. Investigating the Self-Healing Capability of Bituminous Binders. 2011
- [20] Yadykova A, Llyin S. Bitumen improvement with bio-oil and natural or organomodified montmorillonite: Structure, rheology, and adhesion of composite asphalt binders. *Construction and Building Materials*. 2023
- [21] Meagher W, Jo D, Linder E. Method for evaluating implications of climate change for design and performance of flexible pavements, transportation research record. *Journal of the Transportation Research Board*. 2012
- [22] Hasan M, Hiller J, You Z. Effects of mean annual temperature and mean annual precipitation on the performance of flexible pavement using ME design. *International Journal of Pavement Engineering*. 2016
- [23] Tari Y, Shamsabadi S, Birken R, Wang M. Deterioration modeling for condition assessment of flexible pavements considering extreme weather events. In: *Proceedings Volume 9437, Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure*. 2015
- [24] Tsai B, Coleri E, Harvey JT, Monismith CL. Evaluation of AASHTO T 324 Hamburg-wheel track device test. *Construction and Building Materials*. 2016;**114**:248-260. DOI: 10.1016/j.conbuildmat.2016.03.171
- [25] Adwan I, Milad A, Memo Z. Asphalt pavement temperature prediction models: A review. *Applied Science*. 2021
- [26] Datta U, Dessouky S, Papagiannakis AT. Harvesting Thermoelectric Energy from Asphalt Pavements *Transportation*
- [27] Zou G, Xu J, Wu C. Evaluation of factors that affect rutting resistance of asphalt mixes by orthogonal experiment design. *International Journal of Pavement Research and Technology*. 2017;**10**(3):282-288. DOI: 10.1016/j.ijprt.2017.03.008

Chapter 8

Road Markings for Reliable Visual Guidance and Sustainability

Tomasz E. Burghardt

Abstract

Road markings—inalienable elements of almost all paved roads worldwide responsible for the safe guidance of drivers—are described from the perspective of materials. The characteristics of road markings as dual-layer speciality industrial maintenance coatings, along with their key performance parameters, are explained. Results from field and laboratory evaluations of various materials are utilised to present the key issues associated with the visibility of road markings for both human drivers and machine vision equipment. The topic of sustainability is addressed based on the outcome of field tests; the carbon footprint of representative materials from a long-term perspective (i.e., a series of renewals to maintain the properties, as is appropriate in cases of deteriorating systems) is given. The issue of microplastic emissions is discussed; the newest results are used to demonstrate the inadequacies of earlier theoretical estimates. Emerging concepts, such as luminescent road markings, are criticised due to low practical applicability. Good practice recommendations to maximise the properties for road users are given as a reference for road administrators and scientists.

Keywords: glass beads, retroreflectivity, cold plastic, traffic paint, refractive index, structured markings, road safety, visibility, lidar, financial analysis, microplastic

1. Introduction

Road markings (RM), in the form of lines, stripes, or shapes painted on roadway surfaces, have become common over the years on a vast majority of paved roads worldwide. Their main role is increasing road safety through channelling and organising traffic. The effectiveness of RM is enormous; it was calculated that the expenses associated with their installation and maintenance were about sixty-fold lower than the costs of chaotic traffic and accidents in their absence [1]. Literature related to the effect of RM on driver behaviour is plentiful [2]; however, such aspects are beyond the scope of this work. Instead, RM shall be approached herein from the perspective of materials, with particular accent on those that furnish long service life and good visibility. A significant difficulty in this area is a paucity of published reliable research and almost complete disconnection between the reports from North America and the rest of the world; this is caused by North American specifications being based on

materials composition or predefined gradations, with strict limits and restriction of novel materials. As a consequence, research on novel solutions is almost exclusively published in Europe, where the accent on performance allows for greater flexibility and the introduction of solutions more beneficial for the road users.

From a materials perspective, all RM belong to speciality industrial maintenance coatings—they are highly unique because they comprise two vastly dissimilar layers that must cooperate to form the final functional product: a coating/paint layer and a strewn-on retroreflective/glass beads (GB) layer [3, 4]. For effectiveness, RM must be visible to road users (drivers, pedestrians, and also to machine vision sensors)—this is achieved because of the contrasting colour [5–7]; edge detection due to the contrast is the key visual property for road users. At night the contrast is augmented by retroreflectivity—a phenomenon of reflecting back toward the driver the light from the vehicle's headlights. This phenomenon is achieved solely because of the GB and their embedment in the paint layer [8, 9]. The same layer of GB plays a critical role in protecting the paint layer from abrasion by passing vehicles. This dual role of the GB—simultaneously enhancing the visual performance of RM and protecting them from abrasion—is of utmost importance for any environmental assessment and practices of their maintenance.

The first half of this chapter is devoted to the materials (function of both layers of RM), and the second half to the properties (visibility and environmental issues); recommendations for good practices are provided. The critical distinction between the functional and the physical service life is briefly explained [10]. The effects of materials selection on visibility for drivers and machine vision equipment are provided based on the outcome of field experiments. The advantages of new solutions, such as increasing refractive index (RI) of the GB [11] or the use of structured markings permitting moisture drainage and thus enhancing visibility at night under wet conditions, are illustrated [12]. Because RM belong to deteriorating systems that require periodic renewals to maintain functional properties, their sustainability has to be addressed from a long-term perspective [13]. Results from field tests indicated quite large variations in the service life achieved with various materials [14], which affected their consumption and thus their global warming potential (GWP). The values for GWP for representative RM, calculated for environmental product declarations [15], are provided herein as a reference. The current environmental issue of microplastic (MP) pollution is discussed because of the prior misconceptions that resulted in grossly erroneous emission estimates [10, 16]; new data is provided. Emerging concepts in RM technologies, such as luminescent materials that started being researched [17], are critically assessed. Finally, recommendations for the best practices—from materials selection, through requirements, to optimum tender pricing suggestions—are provided. The information provided herein, along with the plethora of references, can be used as a handbook by scientists and by road administrators. Because the quality and visibility of RM were associated with road safety, optimum solutions for the benefit of all road users and with minimised environmental impact can be selected.

2. Road markings: Properties

2.1 Layers and functional properties

Because of the interconnection between functions, materials, and properties, the description of RM is quite difficult. The function of the two layers of RM, some of their properties, and exemplary materials are listed in **Table 1**. In the standard

Layer	Coating/paint	Retroreflective/glass beads (drop-on material)
Functions	Adhesion to road surface. Colour contrasting with the roadway = visibility. Surface for retroreflection. Adhesion surface for the retroreflective layer.	Retroreflection. Protection of the coating layer from abrasion. Skid resistance.
Materials	Paint (solvent-borne, water-borne). Thermoplastic. Cold plastic. Plural component (epoxy, urea, urethane, etc.); solvent-borne or solventless. Tapes.	Glass beads (GB). GBs mixed with anti-skid particles (ASP). ASP alone (special purposes only). Crystalline elements in lieu of GB.
Layer thickness, applied quantity	Thin layer (only flat lines): 0.2–0.4 mm (up to 1.0 mm) from wet film 0.3–0.9 mm/0.4–1.6 kg/m ² . Thick layer (flat lines or structures): 1.0–6.0 mm/1.5–6.0 kg/m ² .	Drop-on application: 0.3–0.5 kg/m ² . Thickness (above the coating layer) 0.1–1.0 mm, resulting from GB (and ASP) diameters of 0.2–1.4 mm (possible range 0.06–2.0 mm).
Application methods	Thin layer: spray. Thick layer (only solventless materials): extrusion, screed, roller, glue.	Drop-on. Pre-manufactured (tapes, some preformed thermoplastic and cold plastic, reflective elements).
Abrasion resistance	Very low – low (except for cold plastic and tapes: very high).	High or very high.

Table 1.
Function and typical characteristics of the layers of road markings [4].

EN 1436 [18] are described various classes of performance and the procedures for their measurements are defined. This standard neither limits the selection of materials nor specifies the locally requested performance. While in many countries these standardised definitions and procedures are followed, in North America there are some variations, particularly related to specifying the composition and testing. Some demands from coating layer materials and methods for their testing are specified in the standard EN 1871 [19]; the same applies to the GB and the anti-skid particles (ASP), which are listed in the standard EN 1423 [20]. One must remember that prior to the use on roads, all RM must undergo field or laboratory testing to assure that their functional parameters are met throughout the intended functional service life period [21, 22].

RM are commonly divided based on the layer thickness into a thin layer (usually <1.0 mm thickness, as applied) and a thick layer (up to 6 mm thickness); while technically appropriate, this division cannot reflect the key property for road users: visibility. Per standard EN 1436 [18], RM are divided based on the visibility under wet conditions into Type I (“do not necessarily have special properties intended to enhance the retroreflection in wet or rainy conditions”) and Type II (“with special properties intended to enhance the retroreflection in wet or rainy conditions”). The Type II characteristics are usually achieved only in structured RM (i.e., thick layer applications composed of three-dimensional random or stochastic structures)

because of improved moisture drainage; however, with proper selection of the GB, it may also be possible to obtain Type II characteristics in flat lines, even though usually the effect is not long-lasting. The external appearance of flat and randomly structured RM is shown in **Figure 1**. A cross-section through the thick layer RM is shown in **Figure 2**.

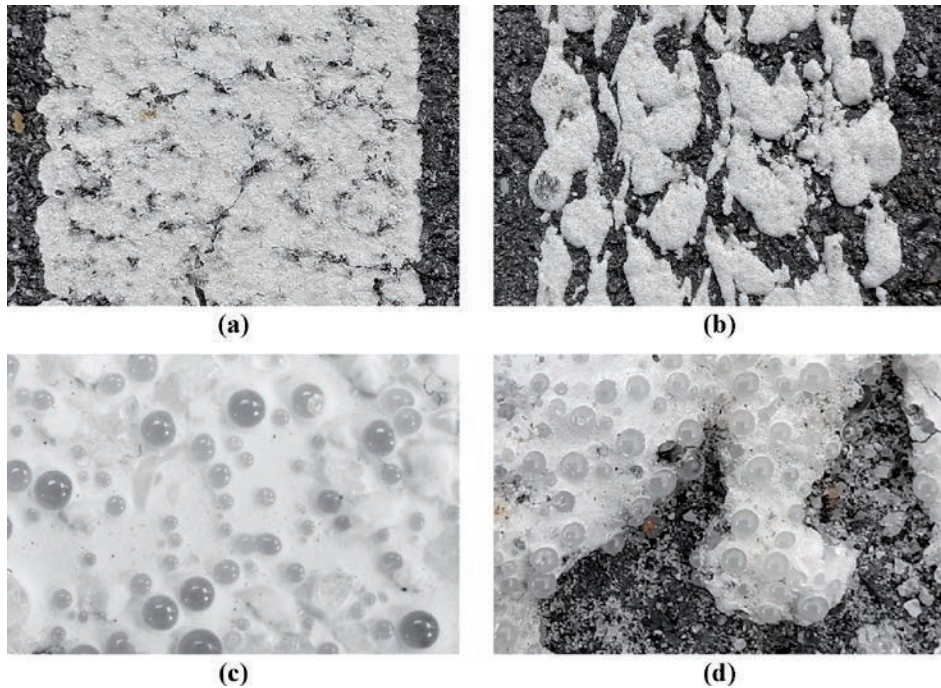


Figure 1.
The external appearance of RM. (a) Type I, flat line; (b) Type II, structure (agglomerates); (c) Close-up of properly embedded GB and ASP in flat line RM; (d) Close-up of GB in structured RM (ASP is not needed because the structure itself provides skid resistance).

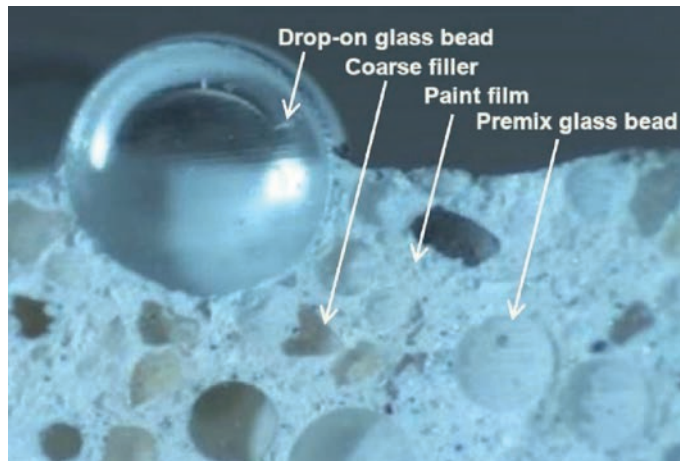


Figure 2.
Cross-section through a thick layer RM [11].

Because only the GB can deliver retroreflectivity and because these same GB are exposed to the tyres of vehicles encroaching on the RM, retroreflectivity is the functional parameter of the RM that in the vast majority of cases fails first and, as such, it controls the length of the functional service life. Retroreflectivity is measured through the coefficient of retroreflected luminance (R_L) and expressed in $\text{mcd}/\text{m}^2/\text{lx}$. The specifications for the typical 30 metre geometry can be found in the standard EN 1436 [18]. Alternative geometries were recently proposed [23], but from a professional perspective, their implementation could create uncertainties and ambiguities that could be disadvantageous for the road users. While R_L can also be reliably measured under the conditions of wetness, measurements under the conditions of rain cannot be currently done in the field, and even the laboratory procedure has not been properly validated despite one testing laboratory issuing certificates. The second important property is daytime visibility, measured as luminance coefficient under diffuse illumination (Q_d) and also expressed in $\text{mcd}/\text{m}^2/\text{lx}$. This parameter is achieved almost solely because of the colour of the paint. There is a connection between Q_d and contrast, but it is not straightforward and depends on factors like lighting, atmospheric conditions, and foremost the surfaces. Skid resistance is another commonly assessed parameter; per standard EN 13036-4 [24], it is measured with a British Pendulum Skid Resistance Tester (SRT) and expressed as a unitless Pendulum Test Value (PTV), sometimes referred to as an SRT value or British Pendulum Number (BPN). Skid resistance is achieved because of the retroreflective layer (particularly when the drop-on GB are intermixed with ASP), but the presence of coarse fillers in the coating layer is equally important.

To properly understand RM, one must consider their life stages [16]:

- Functional service life—the applied RM meet and exceed the minima set in local requirements, particularly R_L .
- Physical service life—the RM no longer meet the prescribed functional properties but remain on the road surface. They may undergo abrasion; only in the case of thermoplastic RM abrasion is advantageous, as it allows for continuous deliverance of R_L .
- End-of-life (erosion)—the RM are physically fully removed from the road surface.

Whereas RM often encroach into the physical service life stage, they seldom reach the erosion stage (minor exceptions by total area, yet quite visible, are areas exposed to heavy traffic like stop lines or pedestrian crossings). This stage is reached through extraordinary conditions, such as (1) the action of turning vehicles that express torque accelerating abrasion, particularly heavy vehicles due to their mass [25]; (2) the action of snow ploughs that physically damage the RM [26]; (3) negligence in maintenance; and/or (4) the use of studded tyres that disrupt the integrity of the coating layer [27]. Mechanical removal of RM is also a rare event, occurring due to excessive thickness of layers or realignment [28]. It must be noted that as long as the GB are present, there is no contact between the tyres and the coating layer — because the tyre tread is approximately ten times larger than the spaces between the drop-on GB, it is physically impossible. Proper selection of materials for RM is important, as the rate of erosion could differ by an order of magnitude [29]. Upon reaching the end of functional service life, RM should be immediately renewed; fresh layers of both paint and GB are used, which results in the stacking of multiple layers.

2.2 Materials

One should observe the multitude of materials for the coating layer listed in **Table 1** and their paucity for the retroreflective layer. Because the most frequently utilised materials were described elsewhere [4, 10], only abridged information is provided herein. The materials for thin-layer RM—applied usually by spraying—can be solvent-borne and water-borne paints or solventless materials like sprayed cold plastic or sprayed thermoplastic. For thick layers, only solventless materials that do not shrink upon curing are used, mostly thermoplastic (delivered as a powdery mass and applied from a hot melt at circa 200°C) and cold plastic (delivered as oligomers and monomers that polymerise on the road surface upon mixing with an initiator). Other solventless materials include plural component systems (used mostly in North America) and tapes (glued to the road surface with a pressure-sensitive adhesive or occasionally applied to hot bitumen). The main ingredients for the coating layer are similar to those that could be found in any other paints [30]. Hazardous ingredients are used very rarely, if ever, due to the requirements set in tenders or regulatory actions. Selected specificities of RM are:

1. Binder—a polymeric material that holds all of the ingredients together; its contents are typically 10–25% (up to 45% in sprayed cold plastic or tapes). Various types of polymers are used, with acrylic, styrenic, hydrocarbon, and alkyd most often employed. Only in the case of thermoplastic RM, a non-polymeric binder derived from rosin, can be used [31].
2. Pigments—in white RM, the most important is TiO_2 [32], which is necessary to form a diffusion cone for retroreflectivity [8]. All white RM contain rutile TiO_2 pigment in the amount of 5–15%. Because TiO_2 has a high carbon footprint [33], there are efforts to have it replaced or reduced; however, because of its high RI and the ability to scatter light instead of absorbing it [32, 34], TiO_2 remains irreplaceable; other materials can be considered only as fillers. It is noteworthy that the alleged carcinogenicity of TiO_2 has not been confirmed in any cohort study [35]; hence, pigment-grade TiO_2 should be considered as safe for the intended use. In other colours, benign organic pigments are used [36] in quantities usually <5%. Toxic pigments like PbCrO_4 are now obsolete due to regulatory and tender demands and their occasionally reported presence in RM is only a residual issue.
3. Fillers—inexpensive and environmentally benign inorganic materials like CaCO_3 , talc, or nepheline syenite [37], comprising the bulk of the material, up to 70%.
4. Coarse fillers—ingredients quite unique to thick layer RM. While acting as fillers, they also modify rheological properties, enhance skid resistance, protect the coating from abrasion, and can even provide retroreflectivity. Inorganic materials with particles usually >0.05 mm (sand, corundum, flint, dolomite) and ‘pre-mix’ GB (diameters usually 0.1–1.0 mm) are used; typical contents are 20–50%.
5. Solvents—volatile organic compounds or water [38], which dissolve the ingredients and allow for application but are not retained in the dry film. Some RM are solventless: in cold plastic, the oligomers and monomers act as a solvent, but instead of evaporating become the polymeric matrix; in thermoplastic all materials are delivered as a powdery mass.

6. Additives—various compounds, polymeric or non-polymeric, organic or inorganic, necessary for processing, application, and final properties; usually comprise <5% of the formulation. In the case of water-borne paints, where the binder is delivered as a dispersion, a coalescent must be used [39].

The materials for the retroreflective layer are much more limited—only GB and ASP are used. While in North America and some other countries, gradation of the GB is set in requirements, in Europe it is the desired performance that determines the used gradation. From a professional perspective, the American approach is faulty as it limits development and does not bring any benefits for the road users. Proper embedment of the GB is important to maximise R_L and to prevent their premature extraction from the film; usually, 50–60% is recommended [8, 9]. The materials for the retroreflective layer should be coated with an organosilane to facilitate adhesion to the coating layer; proper selection of the organosilane is critical [40].

Numerous aspects related to the GB were recently described [11]; thus, only limited information shall be repeated herein. Typical basic properties of GB utilised for RM are listed in **Table 2** (typical R_L values based on the author's laboratory tests in white paint). Crystalline ceramic elements with RI >1.9 are included for comparison, even though they are not known to be applied on-site but are solely used in some high-end Type II tapes. Quite oddly, GB with RI 1.7–1.9 are not known to be broadly manufactured or used for RM; only recently, the first commercial trials in RM were made (professional knowledge). One must observe that the maximum R_L is achieved at RI 1.9 [8]; further increase only brings advantage during wet (or even submerged) conditions [43, 44].

The most advantageous from the perspective of properties appears to be the “Premium” GB, which can provide high R_L , both under dry and wet conditions. The high R_L , achieved because they contain TiO_2 in the glass matrix [45], also allows for the obtention of high R_L in yellow RM [46, 47] and for the preparation of RM with simultaneously high skid resistance and high R_L [48, 49]. An important issue that seems to be preventing the use of “High index” GB in RM, despite outstanding achievable R_L , is their low resistance to scratching [50]. This issue was partially alleviated in the “Premium” GB; despite the measured rate of R_L decay being higher than

Type of GB	“Standard”	“Large”	“Premium”	“High index”	“Ceramic elements”
Refractive index	1.5	1.5	1.6–1.7	1.9	2.1–2.4
Diameters [mm]	0.06–0.85	0.60–2.00	0.30–1.00	0.30–1.00	0.02–0.05
R_L (dry) [mcd/m ² /lx]	350	450	1000	1800	<300
R_L (wet) [mcd/m ² /lx]	60	100	200	400	600
Usage in RM	Typical, premix	Improved wet R_L , rarely premix	High R_L (dry and wet), rarely premix	Airport markings (dry and wet R_L) [41, 42]	High wet R_L (no dry R_L) [43]

Table 2.
 Types and typical properties of GB and crystalline elements used for RM.

with the “Standard” GB, the disproportionately high initial R_L still permitted for the obtention of a prolonged functional service life of RM [14].

To achieve skid resistance, ASP, comprising 10–30% of the retroreflective layer materials, can be intermixed with GB. However, in many cases (especially structured RM), the ASP are not used. The use of ASP without GB is done very seldom and only for special applications, such as racetracks or bicycle paths. Skid resistance is a rarely addressed issue despite its profound importance for the safety of unprotected road users; like in other aspects related to RM, there is a disconnection between Europe and North America [51]. Recent field studies indicated meaningful differences between the ASP; the paucity of available literature was simultaneously reviewed [52].

3. Road markings for road safety: Visibility

For proper function, RM must be visible to all road users, including machine vision equipment employed in driver assistance systems. Visibility is tantamount to contrast, and more specifically to edge detection [5, 6]. Various aspects related to the visibility of RM were quite broadly described in an action report from the European project COST 331 [53]. In spite of its profound importance, the visibility of RM for drivers was studied quite seldom. Tests done with an eye tracker were started in the late 1990s [54]; they were followed by the evaluation of tapes designed for Type II performance [55]. During similar assessment during rainy conditions [56], easier detection of Type II RM was noted by drivers, who considered the enhanced visibility as making the driving task easier and more comfortable. The reduction in crashes during wet weather in the presence of Type II RM was reported [57]. Recently, preview distances of RM with widths of 5–30 cm and R_L of 33–420 mcd/m²/lx were systematically examined [58]. A very good correlation between the preview distances (30–149 m), R_L , and line width was found. Because prior research indicated the benefits of using wider lines [59], this work illustrated that line visibility was also correlated with R_L .

Based on studies of drivers’ visual needs, maintaining $R_L > 150$ mcd/m²/lx has been proposed [60, 61]; nonetheless, the majority of road administrators permit the decrease of R_L to 100 mcd/m²/lx or even less. In the United States, only recently the requirements for minimum R_L , only 50–100 mcd/m²/lx, were introduced. A positive correlation of higher R_L with increased road safety was found based on single-vehicle collision data sets; it was most likely due to the drivers being able to see the RM better [62, 63]. These effects were measured with relatively low R_L , such as can be achieved with ‘standard’ GB; the impact of really high R_L has not been assessed so far because data sets for reliable conclusions are absent.

A comparative analysis of the visibility of a pedestrian crossing marked side-by-side with Type I and Type II materials revealed profound differences, but only during wet conditions at night, as illustrated in **Figure 3** [12]. Whereas the differences were quantified using contrast ratio, it was shown that edge detection played a more significant role than the value of contrast ratio. Hence, prior claims of a minimal contrast needed for driving automation [64] could be dismissed, and simultaneously some reported inconsistencies [65, 66] could be explained.

Yellow or orange RM are quite commonly utilised throughout the world, mostly to separate the directions of traffic or as temporary markings within road work zones, but also for other local purposes. Because they contain only a miniscule quantity of TiO₂ in the paint, much lower R_L is possible than in white paints. Low R_L , along with the resulting

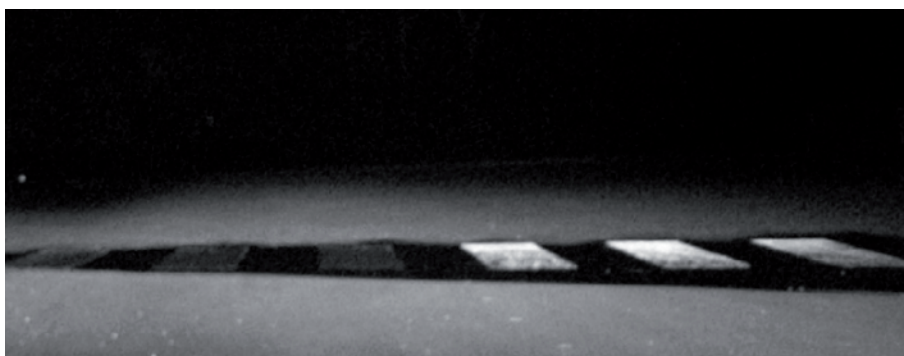


Figure 3.
Comparison in the visibility of RM: Type I (on the left; “Standard” GB, flat lines) and Type II (on the right; “Premium” GB, structured lines) [12].

inadequate contrast, might be an explanation for the reported absence of a safety effect upon the switch to yellow centre lines in the United States [67]. The use of the “Premium” GB could alleviate this issue: field tests done in Switzerland [46] and in Texas [47] confirmed that high R_L under both dry and wet conditions could be achieved.

RM are equally needed by machine vision equipment utilised by driver assistance systems [7, 68]. A straight correlation between R_L of RM and lidar response is well-established [69–71]. In the aforementioned field visibility experiment (Cf. **Figure 3**), lidar was blinded for circa 40 s under wet conditions when Type I material was submerged, but Type II RM were constantly perceived [12]. Driving experiments also confirmed better perception of the Type II RM as compared to Type I by the machine vision [72, 73].

4. Sustainability of road markings

4.1 Service life and carbon footprint

Field experiments with side-by-side testing of numerous thin-layer RM in transverse arrangements permitted for determining the relative effects of both the paint and the GB choice on the length of functional service life; simultaneously, the analysis of the most-used (at wheel track) and least-used (between wheel track) regions allowed for roughly determining the effects of glass beads adhesion [14]. Whereas the choice of coating layer material was shown as controlling the functional service life, the selection of the type of GB played a secondary yet profound role. The properties measured in the field were correlated with the environmental sustainability through calculation of the consumption of the key ingredients [14]. The average effects (data from testing of various materials) are illustrated in **Figure 4**. Of particular importance are the rates of R_L decay, which were found to play a more important role in the functional service life than the initial values; this field study confirmed the outcome from the laboratory [50].

RM are seldom included in life cycle assessments of roadway infrastructure [74, 75], most likely because of their relatively low carbon footprint; some of the assumptions given in such assessments seem dubious based on professional knowledge. Preliminary evaluation of RM indicated that the controlling parameter of their sustainability was the length of the functional service life and not the composition [76, 77]; a rough

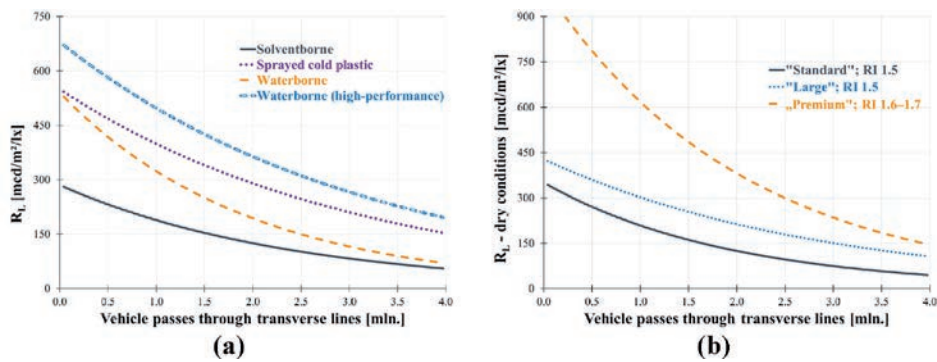


Figure 4. The average effect of paint and GB selection on retroreflectivity retention in thin-layer RM: (a) the choice of paint, (b) the choice of drop-on GB.

evaluation based on the consumption of the key raw materials confirmed the preliminary assessment [14]. Herein, GWP values are provided in **Table 3** for a series of renewals, as is appropriate for deteriorating systems [13]. One must note that the used service life, which was found as the controlling factor, was assumed based on professional knowledge, limited publications [78, 79], and the outcome of the field experiment [14]. The calculations were done for environmental product declarations [15] for modern plants located in Europe, which affected the considerations related to energy, transport, etc. Weaknesses of such analyses are known [80]; hence, the provided values should be considered only as an indication. The issue of MP and other particulate emissions from thermoplastic RM that undergo slow abrasion was not included in the assessment as currently no reliable method is available. Similarly, any effects of RM on road safety were disregarded even though it is the main purpose for the existence of these materials. A very high GWP calculated for the solvent-borne paint was caused solely by the shortest functional service life that such a system afforded. Indeed, a paint labelled as “green” due to the minimised contents of TiO_2 and the absence of toluene solvent has been found to have the highest carbon footprint [14]. Very importantly, the use of RM that, per composition, may appear to be less sustainable (particularly due to the presence of TiO_2 in the “Premium” GB and to the high contents of polymeric binders in sprayed cold plastic), from the long-term perspective was consistently more ecological—that was due to prolonged functional service life. This aspect must always be kept in mind when selecting materials for RM. Interestingly and advantageously, separate calculations indicated that, despite the meaningfully higher unit cost of such materials, the long-term expenses did not increase [46, 81].

4.2 Microplastics

The issue of MP pollution is amongst the most studied current environmental topics; it is not a mature area, as evidenced by the absence of uniform definitions and numerous uncertainties in reporting [82]. The European Union legislators recently attempted to introduce some definitions and regulations aiming at limiting the pollution from secondary MP (i.e., those resulting from the disintegration of larger plastic-containing pieces) [83]. Subjectively, it was argued that some definitions appear to be faulty—particularly the concept of considering a particle containing $>0.01\%$ of a

Initial application ^a	Service life ^b	Renewal application ^a	Service life ^b	Total GWP [kg CO ₂ eq.] ^c
SB + S	1	SB + S	1	66
WHP + S	2	WHP + S	2	30
WHP + P	3	WHP + P	3	22
KSP + S	2	KSP + S	2	30
KSP + P	3	KSP + P	3	22
KP + S	5	SB + S	1	63
KP + S	5	KSP + S	2	38
KP + P	7	KSP + P	3	29
TPH + S	5	TPH + S	5	39
TPR + S	5	TPR + S	5	31

^aSB = solvent-borne paint, 0.6 kg/m²; WHP = high-performance water-borne paint, 0.6 kg/m²; KSP = sprayed cold plastic, 0.5 kg/m²; KP = cold plastic, 6.0 kg/m²; TPH = thermoplastic with polymeric binder, 6.0 kg/m²; TPR = thermoplastic with non-polymeric rosin-based binder, 6.0 kg/m²; S = “Standard” GB, 0.4 kg/m²; P = “Premium” GB, 0.4 kg/m².

^bAssumed functional service life in years.

^cCalculated for 1 m² of marked surface to maintain functional properties for 20 years.

Table 3.
 Assumed service life and sustainability for the period of 20 years.

synthetic polymer as an MP in its entirety; such a definition prevents fair assessment, unnecessarily complicates reporting, and brings no value to anyone [84].

The first report associating MP emissions with RM was published about a decade ago [85]; it contained a warning that data and procedures critical for correct assessment were missing. Unfortunately, the majority of publications that followed did not heed the warning and were flawed by unrealistic assumptions. The distinction between functional and physical service life was ignored, and the protective role of GB was disregarded [10]; consequently, data chaos, gross inconsistencies in reported quantities, and unrealistic estimates abounded [16]. The absence of a reliable analytical method to positively assign MPs originating from RM in the presence of other MPs and variations in reporting that made comparisons impossible created additional confusion [16, 86]. Meanwhile, several researchers indicated finding pieces of RM amongst MP [87–90], which proved that the contamination was real. Nonetheless, examination of these reports revealed that in all of the cases, the extraordinary conditions described earlier (Cf. Section 2.1) were present—mainly grossly negligent maintenance and the usage of studded tyres. Hence, RM may have been unfairly targeted in the assessments, as the found particles appeared to have been a result of improper usage and not their intrinsic properties.

The issue of improper reporting and the absence of field work with RM was tackled by the author of this chapter in several collaborative efforts. Despite publishing the methodology, efforts were not picked up by independent researchers; hence, the reliance on own work herein. After field observations, the contribution of RM to MP emissions was estimated based on erosion at pedestrian crossings. Because such ‘zebra’ stripes are exposed to all the passing vehicles, they can be considered as representing the worst-case scenario. Measurements were done using luminance loss as an indicator of erosion, according to a methodology developed for machine vision technology [91], after slight modifications [10, 31].

The results indicated that the earlier alarming quantities of emissions were grossly overestimated—only <5% of the assessed markings were found to have been eroded (as compared with prior claims of erosion reaching 100%) [10]. In addition to finding low erosion, stacking of layers of RM was evident in all of the analysed cases, as shown in **Figure 5**. Only in Sweden, where studded tyres are used, erosion was

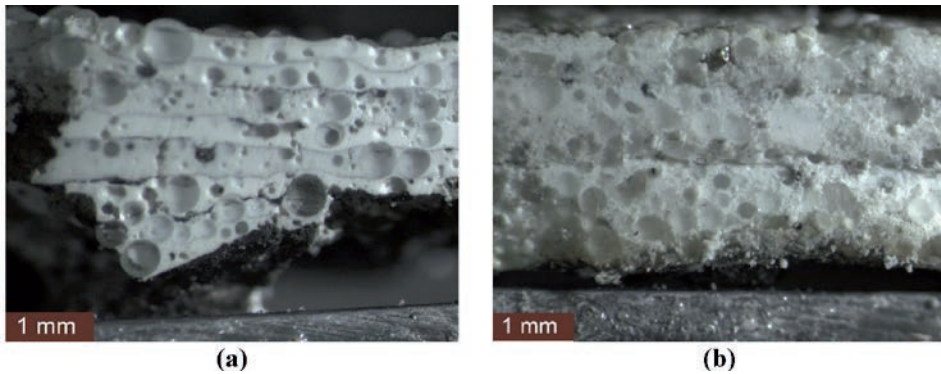


Figure 5. Cross-section of RM samples with multiple layers. (a) Paint (thin layer applications) from Poland; (b) Thermoplastic (thick layer applications) from Sweden.

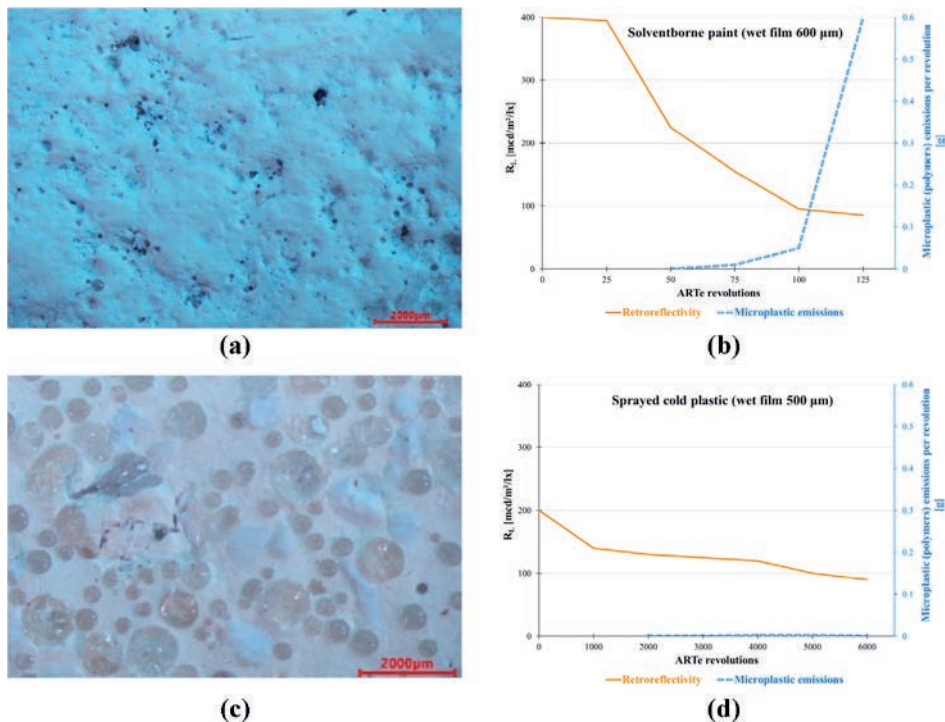


Figure 6. Laboratory study of MP release from RM; two modes of R_L failure and effect on MP emissions. (a) Surface of paint at the end of functional service life, with extracted GB; (b) Emissions of MP from the paint as a function of R_L ; (c) Surface of sprayed cold plastic at the end of functional service life, with retained GB; (d) Emissions of MP from the sprayed cold plastic as a function of R_L .

reaching approximately 20% [10, 31]. Even though such high erosion may be a reason for concern, one should note that in snowbanks in the Arctic region of Sweden, RM constituted <3% of all found MP particles, while tyre and bitumen wear—86%—and other organic debris—10.6% [92]. Elsewhere, an approximately twenty times excess of tyre wear over potential RM wear was also reported [93]. More recent research indicated that grossly negligent maintenance of 25% of the analysed ‘zebra’ stripes was responsible for >80% of the total erosion [94].

The latest study, done in Poland [29], was focused on the rate of erosion of neglected RM. It was shown that while thick layer cold plastic was abrading at the rate of 2.1% per 1.0 million vehicle passes, the rate for paint was 20.2%. Outstanding resistance of cold plastic to abrasion was also noted by a German research institute based on the outcome of 20 years of research at a test field in the Harz mountains; average annual erosion was estimated at <5% [95].

Recent laboratory research using abrasive testing confirmed the protective role of the GB; two modes of R_L failure were shown—extraction of the GB from the film or their mechanical damage. Preliminary results (manuscript submitted) can be seen in **Figure 6**; whereas upon the loss of the drop-on GB, the emissions of MP commenced and quickly reached a high level, upon only surface damage to the drop-on GB and their retention in the film, the MP release remained miniscule despite much higher polymer contents.

5. Emerging concepts

Because RM technologies are well-established and the introduction of a new product demands quite expensive and sometimes time-consuming homologation, there is little novelty; the emerging concepts must become quite mature before commercial introduction. Particularly in North America, where standards are based on composition and not on performance, the marketing of novel materials is quite difficult. The latest new developments that were successfully commercialised appear to be the quick-set water-borne paints and more recently the “Premium” GB.

At present, the most frequently analysed emerging topic seems to be luminescent RM [17]. There is a plethora of published research on developing this technology [96]; strontium aluminate doped with europium is consistently utilised as the luminescent additive [97]. Even though the reported laboratory results indicate some potential and visibility advantages over traditional RM, the cost, the service life [98], and the materials availability were not thoroughly assessed. Only one paper was found where the issue of the expense was considered an important obstacle [99]. Indeed, at present the commercial price for luminescent RM is more than ten times higher than for traditional materials (professional knowledge). The availability of raw materials, particularly europium, must be considered. Furthermore, as with all emerging chemicals, the luminescent pigment has not been thoroughly assessed for possible hazards, and its carbon footprint was not calculated. Thus, even though the idea of RM glowing in the dark may be appalling, it is unlikely to be a commercial success. In addition, because all vehicles are equipped with headlights, the advantage of luminescence may be overestimated, particularly in lit areas [98].

RM that could be cured through exposure to ultraviolet light could bring a great advantage through shortening of the drying time [100]; nonetheless, the concept has not been commercialised. Similarly, the well-established technology of thermochromic pigments was not explored in RM besides a patent [101] and an insignificant

report without a follow-up; hence, RM that would be warning drivers about the risk of slippery roads due to temperatures approaching freezing were not introduced. Amongst other emerging ideas were RM doped with metallic particles to make them visible for radar [102]; while this could have a potential use for driving assistance systems, the currently used automotive radars do not seem to be designed for the recognition of RM as features used for trajectory planning [68].

Recently, a concept of using polymeric prismatic patterns capable of delivering complete retroreflection was developed [103]; nonetheless, broad usage is currently unlikely due to the necessity of installing the reflective elements in pavement grooves to protect them from the traffic and from snow ploughing and the need of cleaning as part of their maintenance. If successful, this would be a completely novel idea of RM, prepared without the GB.

6. Recommendations and conclusions

To simultaneously maximise the benefits for road users and minimise the environmental footprint, the following are recommended:

- Type II structured RM should be used as much as possible. They ought to be mandated for all multi-lane and major roads. Their visibility under wet conditions and generally prolonged service life bring major advantages that cannot be omitted.
- Reflectorisation with GB characterised by RI 1.6–1.7 is suggested to maximise visibility under both dry and wet conditions; the use of GB with even higher RI would be advantageous only if they provide equally long functional service life.
- RM ought to be renewed upon the decrease of R_L to 100–150 mcd/m²/lx. In no case should further deterioration of R_L be permitted because of diminished visibility and the risk of MP emissions from neglected RM.
- Materials that are most durable (i.e., furnish the longest functional and physical service life) ought to always be selected. The enormous measured difference in erosion rate emphasises the necessity of appropriate materials choice for a particular area.
- Because *durability is sustainability*, the “green” products are not those that are labelled as such but those that furnish the longest service life.
- Selection of thermoplastic RM based on biogenic non-polymeric binder is a sustainable choice only if the achieved functional and physical service life under local usage conditions is comparable to that obtained with other technologies.
- Installation of RM in grooves (recessed markings) can bring benefits of preventing the damage by snow ploughs, but there are also disadvantages to such solutions, so a careful approach and individual analysis are needed.
- The requirements set in tenders ought to be high but not unreasonable. Road administrators must understand that certain requirements cannot be met in cases

of extraordinary circumstances (for example, extensive snow ploughing) and that there are certain limitations on materials (for example, simultaneously high R_L and high skid resistance or high R_L in RM other than white).

- Materials should be homologated before being permitted to be utilised (to assure that they are free from hazardous ingredients). The most important is the performance in the field, where the accent on visibility, also under wet conditions, should be placed. Performance parameters must be kept throughout the intended and approved functional service life.
- Long-term performance contracts, in which the applicator can select any homologated materials while the road administrator strictly supervises the performance in the field, appear to be the best solution. It is then in the contractor's own financial interest to select materials that furnish the longest service life. Because such materials were shown to be the sustainable choice (Cf. Section 4.1), even without regulation the environmental protection would be realised and the carbon footprint minimised. The reported negative experience with such a contract in North America was most likely caused by the limitations related to the materials choice and the contract design [104].
- High application quality is absolutely critical. Application crews must be properly trained so maximum properties could be achieved ("poor application shall result in mediocre RM even with the best materials").

RM are so advantageous and effective that their replacement with any currently known technology does not seem possible within the foreseeable future. The advantages of RM include their equal usefulness for human drivers and for machine vision, effectiveness without any external energy source, existing presence worldwide, and known technologies that are generally benign and require only a low carbon footprint. As was demonstrated herein, based on results from field evaluation, the best performance can be expected from structured RM reflectorised with GB characterised by RI 1.6–1.7. Such RM provide not only high R_L during dry conditions but also are visible at night during rain. Simultaneously, due to extended functional service life, environmental impact can be decreased. Hence, not the composition but the service life determines their sustainability. Furthermore, exemplary cost analysis has shown such RM to be the most cost-effective solution from a long-term perspective. The recently studied emerging concepts, particularly the inclusion of luminescent pigments, do not seem to be a feasible choice at present. For effectiveness, RM should be well-maintained and clearly visible to road users. The ultimate goal of installation and maintenance of RM—increase in road safety—must always be kept in mind.

Conflict of interest

The author of this chapter is employed by a company involved in the production of road marking materials and their application. His employer played no role in the selection of references and the presented research results.

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References

- [1] Miller TR. Benefit–cost analysis of lane marking. *Transportation Research Record*. 1995;**1334**:38–45
- [2] Babić D, Fiolić M, Babić D, Gates T. Road markings and their impact on driver behaviour and road safety: A systematic review of current findings. *Journal of Advanced Transportation*. 2020;7843743. DOI: 10.1155/2020/7843743
- [3] Pocock BW, Rhodes CC. Principles of glass-bead reflectorization. *Highway Research Board Bulletin*. 1952;**57**:32–48
- [4] Babić D, Burghardt TE, Babić D. Application and characteristics of waterborne road marking paint. *International Journal for Traffic and Transport Engineering*. 2015;**5**:150–169. DOI: 10.7708/ijtte.2015.5(2).06
- [5] Brémond R. Visual performance models in road lighting: A historical perspective. *Leukos*. 2020;**17**:212–241. DOI: 10.1080/15502724.2019.1708204
- [6] Spieringhs RM, Smet K, Heynderickx I, Hanselaer P. Road marking contrast threshold revisited. *Leukos*. 2022;**18**(4):493–512. DOI: 10.1080/15502724.2021.1993893
- [7] Storsæter AD, Pitera K, McCormack ED. The automated driver as a new road user. *Transport Reviews*. 2020;**41**(5):533–555. DOI: 10.1080/01441647.2020.1861124
- [8] Vedam K, Stoudt MD. Retroreflection from spherical glass beads in highway pavement markings. 2: Diffuse reflection (a first approximation calculation). *Applied Optics*. 1978;**17**(12):1859–1869. DOI: 10.1364/AO.17.001859
- [9] Grosjes T. Retro-reflection of glass beads for traffic road stripe paints. *Optical Materials*. 2008;**30**(10):1549–1554. DOI: 10.1016/j.optmat.2007.09.010
- [10] Burghardt TE, Pashkevich A, Babić D, Mosböck H, Babić D, Żakowska L. Microplastics and road markings: The role of glass beads and loss estimation. *Transportation Research Part D: Transport and Environment*. 2022;**102**:103123. DOI: 10.1016/j.trd.2021.103123
- [11] Burghardt TE. Glass beads for road markings and other industrial applications. In: Vasconcelos HC, editor. *Glass science - innovations and applications*. London: InTech Open. DOI: DOI: 10.5772/intechopen.1009295
- [12] Burghardt TE, Chistov O, Reiter T, Popp R, Helmreich B, Wiesinger F. Visibility of flat line and structured road markings for machine vision. *Case Studies in Construction Materials*. 2023;**18**:e02048. DOI: 10.1016/j.cscm.2023.e02048
- [13] Sánchez-Silva M, Klutke GA. *Reliability and Life-Cycle Analysis of Deteriorating Systems*. Cham: Springer International Publishing; 2016. 371 p. DOI: 10.1007/978-3-319-20946-3
- [14] Burghardt TE, Babić D, Pashkevich A. Sustainability of thin layer road markings based on their service life. *Transportation Research Part D: Transport and Environment*. 2022;**109**:103339. DOI: 10.1016/j.trd.2022.103339
- [15] Achenbach H, Diederichs SK, Wenker JL, Rüter S. Environmental product declarations in accordance with EN 15804 and EN 16485—How to

- account for primary energy of secondary resources? *Environmental Impact Assessment Review*. 2016;**60**:134-138. DOI: 10.1016/j.eiar.2016.04.004
- [16] Burghardt TE, Pashkevich A. Road markings and microplastics – A critical literature review. *Transportation Research Part D: Transport and Environment*. 2023;**119**:103740. DOI: 10.1016/j.trd.2023.103740
- [17] Nance J, Sparks TD. From streetlights to phosphors: A review on the visibility of roadway markings. *Progress in Organic Coatings*. 2020;**148**:105749. DOI: 10.1016/j.porgcoat.2020.105749
- [18] European Standard EN 1436. Road Marking Materials. Road Marking Performance for Road Users and Test Methods. Brussels: European Committee for Standardization; 2018
- [19] European standard EN 1871. Road Marking Materials - Paint, Thermoplastic and Cold Plastic Materials - Physical Properties. Brussels: European Committee for Standardization; 2020
- [20] European Standard DIN EN 1423. Road Marking Materials - Drop on Materials - Glass Beads, Antiskid Aggregates and Mixtures of the Two. Berlin: DIN Deutsches Institut für Normung; 2012
- [21] Keppler R. 15 Jahre Eignungsprüfungen von Markierungssystemen auf der Rundlaufprüfanlage der Bundesanstalt für Straßenwesen [in German]. *Straßenverkehrstechnik*. 2015;**49**(11):575-582
- [22] Zusätzlichen Technischen Vertragsbedingungen und Richtlinien für Markierungen auf Straßen (ZTV-M), 2013. Serie: FGSV, Nr. 341 [in German]. Köln: FGSV Verlag; 2013. p. 66
- [23] Muzet V, Bernasconi J, Iacomussi P, Liandrat S, Greffier F, Blattner P, et al. Review of road surface photometry methods and devices– proposal for new measurement geometries. *Lighting Research and Technology*. 2020;**53**(3):213-229. DOI: 10.1177/1477153520958454
- [24] European Standard EN 13036-4. Road and Airfield Surface Characteristics - Test Methods - Part 4: Method for Measurement of Slip/Skid Resistance of a Surface - the Pendulum Test. Brussels: European Committee for Standardization; 2011
- [25] Rys D, Judycki J, Jaskula P. Analysis of effect of overloaded vehicles on fatigue life of flexible pavements based on weigh in motion (WIM) data. *International Journal of Pavement Engineering*. 2016;**17**(8):716-726. DOI: 10.1080/10298436.2015.1019493
- [26] Hirasawa M, Takemoto A, Kasai S, Aita H. Development of recessed pavement markings that incorporate rumble strips. *Journal of the Eastern Asia Society for Transportation Studies*. 2010;**8**:2032-2047. DOI: 10.11175/easts.8.2032
- [27] Laurinavičius A, Skerys K, Jasiūnienė V, Pakalnis A, Starevičius M. Analysis and evaluation of the effect of studded tyres on road pavement and environment (I). *The Baltic Journal of Road and Bridge Engineering*. 2009;**4**(3):115-122. DOI: 10.3846/1822-427X.2009.4.115-122
- [28] Technical Report CEN/TR 16958. Road Marking Materials. Conditions for Removing/Masking Road Markings. Brussels: European Committee for Standardization; 2017
- [29] Burghardt TE, Pashkevich A. Field study of pedestrian crossings

- deterioration over time: Assessment of microplastics emission from road markings. In: McNally C, Carroll P, Martinez-Pastor B, Ghosh B, Efthymiou M, Valantasis-Kanellos N, editors. *Transport Transitions: Advancing Sustainable and Inclusive Mobility - Proceedings of the 10th TRA Conference*. Dublin Ireland; 2024 Lecture Notes in Mobility book series. Springer; 2025
- [30] Nanetti P. Lackrohstoffkunde. Hannover: Vincentz Network; 2017. p. 227
- [31] Burghardt TE, Pashkevich A, Piegza A, Krawiec A. Thermoplastic road markings – Description and microplastic pollution estimate in Sweden. *Journal of Environmental Management*. 2023;**348**:119183. DOI: 10.1016/j.jenvman.2023.119183
- [32] Braun JH, Baidins A, Marganski RE. TiO₂ pigment technology: A review. *Progress in Organic Coatings*. 1992;**20**(2):105-138. DOI: 10.1016/0033-0655(92)80001-D
- [33] Hassan M. Life-cycle assessment of titanium dioxide coatings. In: *Construction Research Congress*; 5-7 April 2009. Seattle. ASCE; 2009. pp. 836-845. DOI: 10.1061/41020(339)85
- [34] de Jong H, Flapper J. Titanium dioxide: Ruling opacity out of existence? *European Coatings Journal*. 2017;**10**:52-55
- [35] Le HQ, Tomenson JA, Warheit DB, Fryzek JP, Golden AP, Ellis ED. A review and meta-analysis of occupational titanium dioxide exposure and lung cancer mortality. *Journal of Occupational and Environmental Medicine*. 2018;**60**(7):e356-e367. DOI: 10.1097/JOM.0000000000001314
- [36] Stratmann H, Hellmund M, Veith U, End N, Teubner W. Indicators for lack of systemic availability of organic pigments. *Regulatory Toxicology and Pharmacology*. 2020;**115**:104719. DOI: 10.1016/j.yrtph.2020.104719
- [37] Wypych G. *Handbook of Fillers*. Toronto: ChemTec Publishing; 2010. p. 752
- [38] Burghardt TE, Pashkevich A. Emissions of volatile organic compounds from road marking paints. *Atmospheric Environment*. 2018;**193**:153-157. DOI: 10.1016/j.atmosenv.2018.08.065
- [39] van der Kooij HM, Sprakel J. Watching paint dry; more exciting than it seems. *Soft Matter*. 2015;**11**(32):6353-6359. DOI: 10.1039/C5SM01505G
- [40] Plueddemann EP. *Silane Coupling Agents*. New York: Plenum Press; 1982. p. 235. DOI: 10.1007/978-1-4899-0342-6
- [41] Pike AM, Datta S. Effect of glass bead refractive index on pavement marking retroreflectivity considering passenger vehicle and airplane geometries. *Transportation Research Record*. 2020;**2674**(10):438-447. DOI: 10.1177/0361198120935869
- [42] Wan Z, Wang H. Retroreflectivity-based service life and life-cycle cost analysis of airfield pavement markings. *Transportation Research Record*. 2024; in press. DOI: 10.1177/03611981241255368
- [43] Burns D, Hedblom T, Miller T. Modern pavement marking systems: Relationship between optics and nighttime visibility. *Transportation Research Record*. 2007;**2056**:43-51. DOI: 10.3141/2056-06
- [44] Shin SY, Lee JI, Chung WJ, Choi YG. Correlations between refractive index and retroreflectance of glass beads for use in road-marking applications

under wet conditions. *Current Optics and Photonics*. 2019;**3**(5):423-428. DOI: 10.3807/COPP.2019.3.5.423

[45] Schultz PC. Binary titania-silica glasses containing 10 to 20 wt% TiO₂. *Journal of the American Ceramic Society*. 1976;**59**(5-6):214-219. DOI: 10.1111/j.1151-2916.1976.tb10936.x

[46] Burghardt TE, Pashkevich A, Mosböck H. Yellow pedestrian crossings: From innovative technology for glass beads to a new retroreflectivity regulation. *Case Studies on Transport Policy*. 2019;**7**(4):862-870. DOI: 10.1016/j.cstp.2019.07.007

[47] Burghardt TE, Maki E, Pashkevich A. Yellow thermoplastic road markings with high retroreflectivity: Demonstration study in Texas. *Case Studies in Construction Materials*. 2021;**14**:e00539. DOI: 10.1016/j.cscm.2021.e00539

[48] Coves-Campos A, Bañón L, Coves-García J, Ivorra S. In situ study of road marking durability using glass microbeads and antiskid aggregates as drop-on materials. *Coatings*. 2018;**8**(10):371. DOI: 10.3390/coatings8100371

[49] Chen J, Li R, Zhang Y, Wu Y, He H. Study on the reflective principle and long-term skid resistance of a sustainable hydrophobic hot-melt marking paint. *Sustainability*. 2023;**15**(13):9950. DOI: 10.3390/su15139950

[50] Wenzel KM, Burghardt TE, Pashkevich A, Buckermann WA. Glass beads for road markings: Surface damage and retroreflection decay study. *Applied Sciences*. 2022;**12**(4):2258. DOI: 10.3390/app12042258

[51] Bao J, Zhao H, Jiang Y, Li S. International perspectives on skid

resistance requirements for pavement markings: A comprehensive synthesis and analysis. *Lubricants*. 2025;**13**(1):29. DOI: /10.3390/lubricants13010029

[52] Burghardt TE, Köck B, Pashkevich A, Fasching A. Skid resistance of road markings: Literature review and field test results. *Roads and Bridges*. 2023;**22**:141-164. DOI: 10.7409/rabdim.023.007

[53] COST 331 – Requirements for Horizontal Road Marking. Luxembourg: Office for Official Publications of the European Communities; 1999

[54] Schnell T, Zwahlen H. Driver preview distances at night based on driver eye scanning recordings as a function of pavement marking retroreflectivities. *Transportation Research Record*. 1999;**1692**:129-141. DOI: 10.3141/1692-14

[55] Burns D, Hodson N, Haunschild D, May D. Pavement marking photometric performance and visibility under dry, wet, and rainy conditions: Pilot field study. *Transportation Research Record*. 2006;**1973**:113-119. DOI: 10.3141/1973-16

[56] Diamandouros K, Gatscha M. Rainvision: The impact of road markings on driver behaviour-wet night visibility. *Transportation Research Procedia*. 2016;**14**:4344-4353. DOI: 10.1016/j.trpro.2016.05.356

[57] Park ES, Carlson PJ, Pike A. Safety effects of wet-weather pavement markings. *Accident Analysis and Prevention*. 2019;**133**:105271. DOI: 10.1016/j.aap.2019.105271

[58] Guan Y, Hu J, Wang R, Cao Q, Xie F. Research on the nighttime visibility of white pavement markings. *Heliyon*. 2024;**10**:e36533. DOI: 10.1016/j.heliyon.2024.e36533

- [59] Park ES, Carlson PJ, Porter RJ, Andersen CK. Safety effects of wider edge lines on rural, two-lane highways. *Accident Analysis and Prevention*. 2012;**48**:317-325. DOI: 10.1016/j.aap.2012.01.028
- [60] Lee H-S, Oh H-U. Minimum retroreflectivity for pavement markings by driver's static test response. *Journal of the Eastern Asia Society for Transportation Studies*. 2005;**6**:1089-1099. DOI: 10.11175/easts.6.1089
- [61] Gibbons RB, Williams B, Cottrell B. The refinement of drivers' visibility needs during wet night conditions. *Transportation Research Record*. 2012;**2272**:113-120. DOI: 10.3141/2272-13
- [62] Avelar RE, Carlson PJ. Link between pavement marking retroreflectivity and night crashes on Michigan two-lane highways. *Transportation Research Record*. 2014;**2404**:59-67. DOI: 10.3141/2404-07
- [63] Carlson PJ, Avelar RE, Park ES, Kang DH. Nighttime safety and pavement marking retroreflectivity on two-lane highways: Revisited with North Carolina data. In: *Proceedings of Transportation Research Board 94th Annual Meeting*; 11-15 January 2015. Washington: Transportation Research Board; 2015. p. 15-5753
- [64] Carlson PJ, Poorsartep M. Enhancing the roadway physical infrastructure for advanced vehicle technologies: A case study in pavement markings for machine vision and a road map toward a better understanding. In: *Proceedings of Transportation Research Board 96th Annual Meeting*; 8-12 January 2017. Washington: Transportation Research Board; 2017. p. 17-06250
- [65] Storsæter AD, Pitera K, McCormack E. Using ADAS to future-proof roads—Comparison of fog line detection from an in-vehicle camera and mobile retroreflectometer. *Sensors*. 2021;**21**(5):1737. DOI: 10.3390/s21051737
- [66] El Krine A, Redondin M, Girard J, Heinkele C, Stresser A, Muzet V. Does the condition of the road markings have a direct impact on the performance of machine vision during the day on dry roads? *Vehicles*. 2023;**5**(1):286-305. DOI: 10.3390/vehicles5010016
- [67] Johns RC, Matthias JS. Relationship of the color of the highway centerline stripe to the accident rate in Arizona. *Transportation Research Record*. 1977;**643**:32-36
- [68] Kuutti S, Fallah S, Katsaros K, Dianati M, Mccullough F, Mouzakitis A. A survey of the state-of-the-art localization techniques and their potentials for autonomous vehicle applications. *IEEE Internet of Things Journal*. 2018;**5**(2):829-846. DOI: 10.1109/JIOT.2018.2812300
- [69] Ai C, Tsai YJ. An automated sign retroreflectivity condition evaluation methodology using mobile LIDAR and computer vision. *Transportation Research Part C: Emerging Technologies*. 2016;**63**:96-113. DOI: 10.1016/j.trc.2015.12.002
- [70] Soilán M, González-Aguilera D, del Campo-Sánchez A, Hernández-López D, Del Pozo S. Road marking degradation analysis using 3D point cloud data acquired with a low-cost mobile mapping system. *Automation in Construction*. 2022;**141**:104446. DOI: 10.1016/j.autcon.2022.104446
- [71] Burghardt TE, Popp R, Helmreich B, Reiter T, Böhm G, Pitterle G, et al. Visibility of various road markings for machine vision. *Case Studies in*

- Construction Materials. 2021;**15**:e00579. DOI: 10.1016/j.cscm.2021.e00579
- [72] Zhao Y, Burghardt TE, Li H, Rosenberger P, Babić D, Babić D, et al. Enhancing LiDAR reliability through utilisation of premium road marking materials. *IEEE Sensors Journal*. 2024;**24**(6):8015-8025. DOI: 10.1109/JSEN.2024.3359754
- [73] Biermeier S, Kemper D, Burghardt T, Garcia-Hernandez A. Machine detectability of road markings using classical image processing techniques for demand-oriented road operations in automated vehicles. *Journal of Traffic and Transportation Engineering (English Edition)*. 2025
- [74] Trigaux D, Wijnants L, De Troyer F, Allacker K. Life cycle assessment and life cycle costing of road infrastructure in residential neighbourhoods. *International Journal of Life Cycle Assessment*. 2017;**22**:938-951. DOI: 10.1007/s11367-016-1190-x
- [75] Verán-Leigh D, Larrea-Gallegos G, Vázquez-Rowe I. Environmental impacts of a highly congested section of the pan-American highway in Peru using life cycle assessment. *International Journal of Life Cycle Assessment*. 2019;**24**:1496-1514. DOI: 10.1007/s11367-018-1574-1
- [76] Cruz M, Klein A, Steiner V. Sustainability assessment of road marking systems. *Transportation Research Procedia*. 2016;**14**:869-875. DOI: 10.1016/j.trpro.2016.05.035
- [77] Burghardt TE, Pashkevich A, Żakowska L. Influence of volatile organic compounds emissions from road marking paints on ground-level ozone formation: Case study of Kraków, Poland. *Transportation Research Procedia*. 2016;**14**:714-723. DOI: 10.1016/j.trpro.2016.05.338
- [78] Karimzadeh A, Shoghli O. Predictive analytics for roadway maintenance: A review of current models, challenges, and opportunities. *Civil Engineering Journal*. 2020;**6**(3):602-625. DOI: 10.28991/cej-2020-03091495
- [79] Idris II, Mousa M, Hassan M, Carlson P, Greyson E. Development of a machine-learning based tool to predict retroreflectivity of pavement markings across the U.S. *Transportation Research Record*. 2025. DOI: 10.1177/03611981241287196
- [80] Konradsen F, Hansen KSH, Ghose A, Pizzol M. Same product, different score: How methodological differences affect EPD results. *The International Journal of Life Cycle Assessment*. 2024;**29**(2):291-307. DOI: 10.1007/s11367-023-02246-x
- [81] Burghardt TE, Pashkevich A. Materials selection for structured horizontal road markings: Financial and environmental case studies. *European Transport Research Review*. 2020;**12**:11. DOI: 10.1186/s12544-020-0397-x
- [82] Hartmann NB, Hüffer T, Thompson RC, Hassellöv M, Verschoor A, Daugaard AE, et al. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environmental Science and Technology*. 2019;**53**(3):1039-1047. DOI: 10.1021/acs.est.8b05297
- [83] Commission regulation (EU) 2023/2055 of 25 September 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as Regards Synthetic Polymer Microparticles. *Official Journal of the European Union*; 2023;L 238/67

- [84] Burghardt TE, Pashkevich A. Rebuttal to “reply to road markings and microplastics...” by Järslskog et al. *Transportation Research Part D: Transport and Environment*. 2024;**134**:104344. DOI: 10.1016/j.trd.2024.104344
- [85] Sundt P, Schulze P-E, Syversen F. Sources of Microplastics-Pollution to the Marine Environment. Report M-321. Oslo: Miljødirektoret; 2014
- [86] He B, Shi C, Chen B, Wu H, Goonetilleke A, Liu A. Occurrence and risk associated with urban road-deposited microplastics. *Journal of Hazardous Materials*. 2023;**459**:132012. DOI: 10.1016/j.jhazmat.2023.132012
- [87] Horton AA, Svendsen C, Williams RJ, Spurgeon DJ, Lahive E. Large microplastic particles in sediments of tributaries of the river Thames, UK – Abundance, sources and methods for effective quantification. *Marine Pollution Bulletin*. 2017;**114**(1):218-226. DOI: 10.1016/j.marpolbul.2016.09.004
- [88] Vijayan A, Österlund H, Magnusson K, Marsalek J, Viklander M. Microplastics (MPs) in urban roadside snowbanks: Quantities and dynamics of release. *Science of the Total Environment*. 2022;**851**(2):158306. DOI: 10.1016/j.scitotenv.2022.158306
- [89] Järslskog I, Jaramillo-Vogel D, Rausch J, Perseguers S, Gustafsson M, Strömvall AM, et al. Differentiating and quantifying carbonaceous (tire, bitumen, and road marking wear) and non-carbonaceous (metals, minerals, and glass beads) non-exhaust particles in road dust samples from a traffic environment. *Water, Air, and Soil Pollution*. 2022;**233**:375. DOI: 10.1007/s11270-022-05847-8
- [90] West-Clarke Z, Turner A. Contamination of Thames estuary sediments by retroreflective glass microbeads, road marking paint fragments and anthropogenic microfibrils. *Science of the Total Environment*. 2024;**912**:169257. DOI: 10.1016/j.scitotenv.2023.169257
- [91] Veit T, Tarel JP, Nicolle P, Charbonnier P. Evaluation of road marking feature extraction. In: *Proceedings of 11th International IEEE Conference on Intelligent Transportation Systems*; 12-15 October 2008. Beijing: IEEE; 2008. pp. 174-181. DOI: 10.1109/ITSC.2008.4732564
- [92] Blomqvist G, Järslskog I, Gustafsson M, Polukarova M, Andersson-Sköld Y. Microplastics in Snow in Urban Traffic Environments. VTI rapport 1171A. Linköping: VTI; 2023
- [93] Magnusson K, Eliasson K, Fråne A, Haikonen K, Hultén J, Olshammar M, et al. Swedish Sources and Pathways for Microplastics to the Marine Environment. A Review of Existing Data. Report C 183. Stockholm: IVL; 2016
- [94] Burghardt TE, Babić D, Kućina I, Babić D. Erosion of road markings in Croatia and estimate of contribution to microplastic pollution. *Transportation Research Procedia*. 2025;**83**:561-568. DOI: 10.1016/j.trpro.2025.03.026
- [95] Microplastic Emission from Road Markings in Germany and Austria. Bad Sachsa: Deutsche Studiengesellschaft für Straßenmarkierungen; 2022. Available from: https://dsogs.de/data/CMM_Contents/files/ForsChung-Mitteilungen/MiCroplastiC-Emmission-from-Road-Markings-in-Germany-and-Austria.pdf [Accessed: December 7, 2022]
- [96] Lin H, Chen F, Zhang H. Active luminous road markings: A comprehensive review of technologies, materials, and challenges. *Construction*

and Building Materials. 2023;**363**:129811. DOI: 10.1016/j.conbuildmat.2022.129811

[97] Nance J, Sparks TD. Comparison of coatings for SrAl_2O_4 : Eu^{2+} , Dy^{3+} powder in waterborne road striping paint under wet conditions. *Progress in Organic Coatings*. 2020;**144**:105637. DOI: 10.1016/j.porgcoat.2020.105637

[98] Villa C, Eymond F, Marquet PL, Brémond R, Saint-Jacques E. Method to predict the performance of luminescent road markings over a year. *Results in Engineering*. 2024;**24**:103388. DOI: 10.1016/j.rineng.2024.103388

[99] Yi Y, Lee M, Choi K. Effectiveness analysis of phosphorescent pavement markings for improving visibility and design standards: Focusing on expressway accident hot spots. *Journal of the Korean Society of Civil Engineers*. 2016;**36**(4):685-694. DOI: 10.12652/Ksce.2016.36.4.0685

[100] Ghiglione G. Photocurable Compositions for Road Marking Paint. Patent Application EP1995285A1. München: European Patent Office; 2008

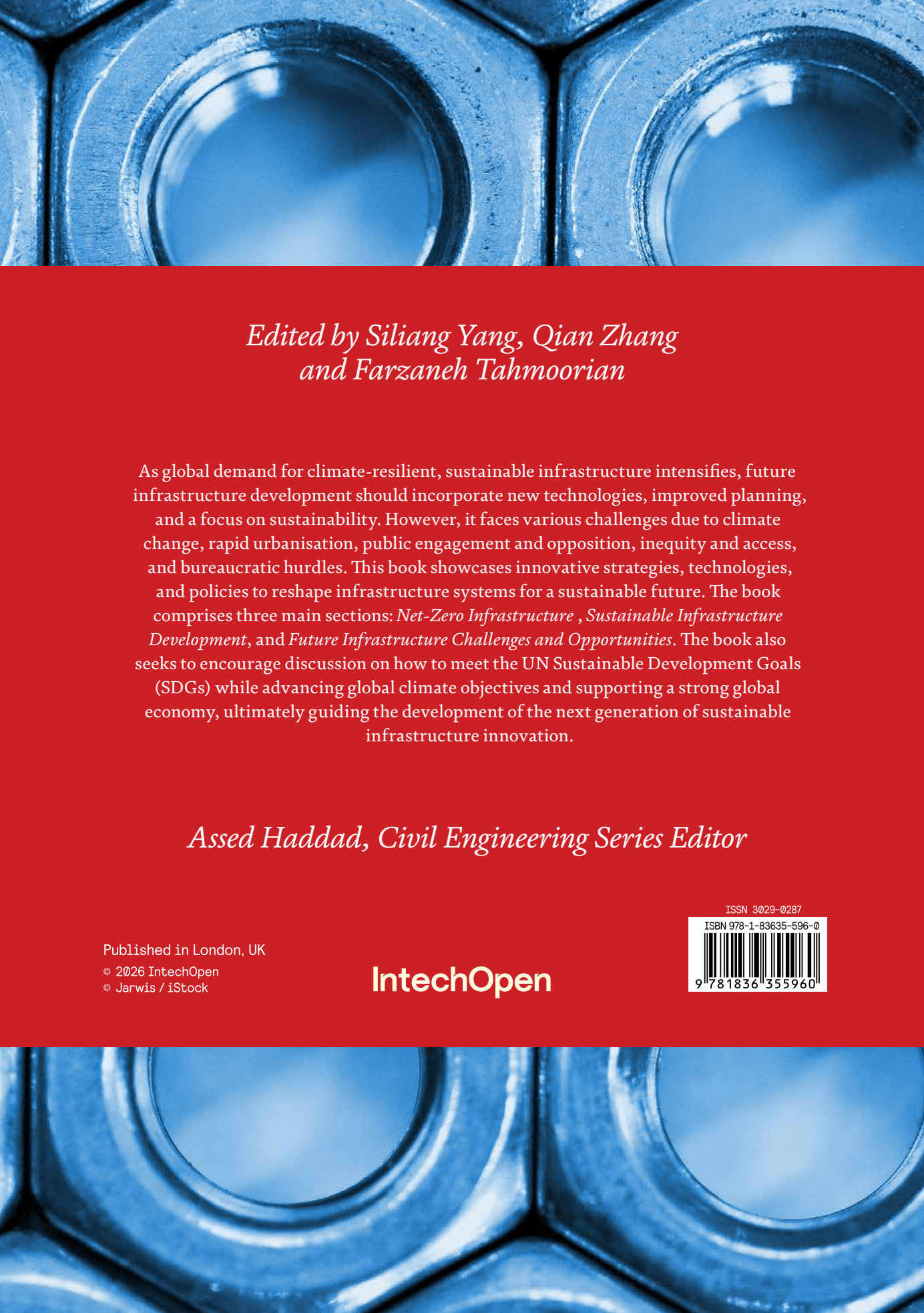
[101] Ravnskjaer N, Moth P, Ogemark T. Method of Making a Road Marking Material with Thermochromic Colouring User Interfaces. Patent Application US 10/929,105. Washington: United States Patent and Trademark Office; 2004

[102] Feng Z, Li M, Stolz M, Kunert M, Wiesbeck W. Lane detection with a high-resolution automotive radar by introducing a new type of road marking. *IEEE Transactions on Intelligent Transportation Systems*. 2018;**20**(7):2430-2447. DOI: 10.1109/TITS.2018.2866079

[103] O'Neill MJ. A Retroreflective Road Lane Marking Tape 1,000X Brighter than Existing Technology. IDEA Program

Final Report for Subaward No. NCHRP-228. Washington: Transportation Research Board; 2022

[104] Damnjanovic I, Pike A, Martinez E. Analysis of performance-based pavement markings and markers contracts: Case study from San Antonio. *Journal of Management in Engineering*. 2017;**34**(2):05017010. DOI: 10.1061/(ASCE)ME.1943-5479.0000574



*Edited by Siliang Yang, Qian Zhang
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As global demand for climate-resilient, sustainable infrastructure intensifies, future infrastructure development should incorporate new technologies, improved planning, and a focus on sustainability. However, it faces various challenges due to climate change, rapid urbanisation, public engagement and opposition, inequity and access, and bureaucratic hurdles. This book showcases innovative strategies, technologies, and policies to reshape infrastructure systems for a sustainable future. The book comprises three main sections: *Net-Zero Infrastructure*, *Sustainable Infrastructure Development*, and *Future Infrastructure Challenges and Opportunities*. The book also seeks to encourage discussion on how to meet the UN Sustainable Development Goals (SDGs) while advancing global climate objectives and supporting a strong global economy, ultimately guiding the development of the next generation of sustainable infrastructure innovation.

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