

Digital Twin Modeling of Asphalt Mixture Microstructures for Performance-Oriented Pavement Design

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Abstract

Asphalt pavements are socio-technical infrastructures whose performance emerges from interactions among aggregate morphology, binder rheology, air-void distribution, compaction energy, climate, and traffic loading. Conventional mixture design often abstracts away mesoscale heterogeneity, treating asphalt as a homogeneous continuum or relying on empirical relationships. This paper develops a system-level research agenda for digital twin modeling of asphalt mixture microstructures to support performance-oriented pavement design. The digital twin is framed not merely as a simulation asset but as an institutional and computational infrastructure that couples imaging, sensing, data governance, physics-based simulation, machine learning, and life-cycle decision-making. The paper examines architectural trade-offs involving fidelity, latency, cost, scalability, uncertainty, and robustness. It discusses how image recognition and tomography can reconstruct aggregate skeletons, mastic films, and void networks, and how these representations can be updated through field data. Deployment challenges in departments of transportation, contractor organizations, and material suppliers are analyzed, including data ownership, model validation, interoperability, and fairness in resource allocation. Sustainability implications are explored through life-cycle assessment and circular material use, while policy implications focus on standards, procurement, and accountability. The paper concludes that digital twin modeling can improve pavement performance prediction only if technical accuracy is matched by governance capacity, transparent uncertainty communication, and equitable institutional design. It proposes a research and policy roadmap for integrating microstructure-aware digital twins into performance-oriented pavement design without reducing them to isolated computational tools.

Keywords

digital twin; asphalt mixture; microstructure; performance-oriented pavement design; image recognition; infrastructure governance; life-cycle assessment; uncertainty.

1. Introduction

Asphalt pavements constitute a critical layer of transportation infrastructure, supporting freight movement, daily mobility, and economic connectivity. Their design and management have traditionally been shaped by empirical test methods, volumetric mixture design, and standardized performance tests that provide aggregate indicators of durability, rutting resistance, fatigue life, and low-temperature cracking. While these methods have enabled reliable highway networks, they often obscure the microscale mechanisms that govern material behavior. Aggregate shape, surface texture, angularity, orientation, void connectivity, mastic distribution, and interfacial bonding collectively determine how asphalt mixtures respond to mechanical and environmental loads. A performance-oriented paradigm therefore requires models that can represent these microstructural features and connect them to pavement-scale outcomes. Digital twin modeling offers one such framework, but its value depends on how it is conceived, governed, and deployed within existing infrastructure institutions.

The digital twin concept originated in manufacturing and aerospace as a virtual representation of a physical asset that is continuously updated with operational data [1]. Early formulations emphasized lifecycle management, simulation, and the mitigation of emergent behavior in complex systems [1]. Subsequent research expanded the concept into Industry 4.0, where digital twins integrate sensors, models, and data analytics across production systems [2]. Classification studies have distinguished digital models, digital shadows, and digital twins according to the degree and direction of data flow between physical and virtual entities [3]. Aerospace applications demonstrated the potential of twinning for structural life prediction and condition-based maintenance [4]. However, pavement systems differ from isolated manufactured products because they are distributed, exposed, public, and governed through multi-organizational arrangements. A digital twin of asphalt microstructure must therefore address not only physics and computation but also institutional coordination, data rights, validation, and equity.

This paper argues that digital twin modeling of asphalt mixture microstructures should be treated as a socio-technical infrastructure for performance-oriented pavement design. The central challenge is not simply to create high-resolution images or sophisticated simulations. It is to design an architecture that links mesoscale material representations to design decisions, construction practices, maintenance strategies, and policy objectives. The paper examines this challenge through several dimensions. It clarifies the conceptual foundations of digital twins in the context of heterogeneous materials. It discusses sensing, image recognition, and data architecture for microstructure characterization. It analyzes computational trade-offs involving fidelity, latency, scalability, and uncertainty. It considers integration with performance-oriented design and life-cycle governance. It explores deployment, robustness, sustainability, and fairness. Finally, it examines policy, standards, and institutional implications.

2. Conceptual Foundations of Digital Twins for Asphalt Microstructures

A digital twin of asphalt mixture microstructure is not a single model but a layered system of representations. At the lowest layer, imaging and tomographic methods reconstruct the spatial arrangement of aggregates, binder, air voids, and additives. At an intermediate layer, computational mechanics and machine learning estimate local stresses, strains, damage evolution, moisture transport, and aging. At a higher layer, these estimates inform pavement design, construction quality control, maintenance scheduling, and lifecycle assessment. The twin becomes digital when these layers are connected through data flows that allow the virtual

representation to update as the physical material changes. It becomes a twin rather than a shadow when information flows bidirectionally and influences decisions in the physical world [3]. This distinction matters for asphalt because a purely analytical model of microstructure may be scientifically valuable but institutionally inert unless it changes specifications, acceptance testing, or maintenance practice.

Asphalt mixtures present a particularly difficult object for digital twinning because their microstructure is stochastic, multiscale, and path-dependent. Aggregate particles are irregular and heterogeneous; binder films vary in thickness; air voids form complex networks; and compaction, aging, and moisture exposure alter these features over time. Image analysis has long been used to characterize internal structure and aggregate arrangement in asphalt concrete [5]. Recent work using image recognition technology has demonstrated how coarse aggregate morphology influences meso-structure, reinforcing the need for microstructure-aware models [6]. Computed tomography has enabled three-dimensional visualization of compaction effects and void distribution [7]. Other studies have examined how aggregate particles affect mastic and air voids, showing that local material organization cannot be reduced to bulk volumetric averages [8]. Micromechanical analyses have also been used to study cracking and damage initiation at the mesoscale [9]. These studies collectively indicate that performance prediction can benefit from representations that preserve spatial heterogeneity rather than smoothing it away.

The conceptual foundation of a microstructure digital twin therefore rests on a representational trade-off. Higher fidelity can capture particle-to-particle contact, mastic films, and void connectivity, but it also increases computational cost, data volume, and calibration burden. Lower fidelity may support rapid screening, but it can miss mechanisms that dominate fatigue, rutting, or moisture damage. A digital twin architecture must decide which features are essential for a given decision context. For example, mixture design may require detailed aggregate shape and gradation representation, while network-level maintenance may only need reduced-order indicators derived from those details. This suggests a modular design in which high-fidelity microstructure models generate surrogate indicators that can be used in pavement management systems. Such modularity also supports uncertainty propagation, because errors in image segmentation, material properties, and loading assumptions can be traced through the model chain.

Another foundational issue is the temporal dimension. Asphalt mixtures age chemically and mechanically. Binder stiffness increases, relaxation capacity decreases, and oxidative aging alters adhesive and cohesive properties [11]. Polymer modification can further change rheological behavior and damage resistance [12]. Reclaimed asphalt pavement introduces aged binder and heterogeneity that complicates prediction [13]. A digital twin must therefore represent not only initial microstructure but also its evolution under traffic, climate, and maintenance interventions. Without a temporal architecture, the twin risks becoming a static snapshot rather than a living representation.

3. Microstructural Sensing, Image Recognition, and Data Architecture

The sensing layer of an asphalt microstructure digital twin includes laboratory imaging, X-ray computed tomography, scanning electron microscopy, optical microscopy, and emerging field-deployable nondestructive methods. Laboratory methods can provide high-resolution representations of aggregate shape, orientation, void structure, and mastic distribution. Image recognition and computer vision can automate segmentation and feature extraction, reducing manual effort and improving reproducibility [6]. Tomographic methods can capture three-

dimensional internal structure that two-dimensional images miss, especially void connectivity and aggregate contact [7]. Dynamic modulus simulation using tomographic images further demonstrates how imaging can feed mechanical prediction [10]. However, these methods generate large datasets and require careful calibration. Segmentation errors, threshold choices, and reconstruction artifacts can propagate into mechanical predictions. A robust data architecture must therefore include metadata, provenance, uncertainty estimates, and versioning.

The data architecture should be designed for interoperability across laboratories, contractors, and transportation agencies. If each organization uses different imaging protocols, file formats, and feature definitions, digital twins will remain siloed. Conversely, standardized ontologies for aggregate morphology, binder properties, void metrics, and test conditions can enable comparative analysis and model reuse. Such ontologies must balance specificity with flexibility, because asphalt materials vary by region, climate, and local aggregate sources. A federated data model may be appropriate: agencies and suppliers retain control of proprietary data while contributing derived features to shared models. This approach raises governance questions about who can access data, how derived value is shared, and how model improvements are attributed. Without clear governance, data sharing may stall or become inequitable.

Machine learning can complement physics-based simulation by learning mappings from microstructure features to performance indicators. For example, convolutional neural networks can classify aggregate shape or detect cracks in images, while surrogate models can approximate expensive finite-element simulations. These methods are attractive because they can reduce computation time and enable real-time or near-real-time decision support. However, they also introduce risks of overfitting, distribution shift, and opaque decision-making. A digital twin that relies on black-box models may be difficult to validate for regulatory acceptance. Hybrid approaches that combine mechanistic constraints with data-driven correction are more likely to earn institutional trust. Such approaches can also support uncertainty quantification by separating aleatoric variability from model-form uncertainty.

The sensing and data layer must also address the reality of field variability. A laboratory specimen represents a small sample of a mixture that may be produced across many plants, placed by different crews, and exposed to heterogeneous conditions. Field sensors can provide temperature, moisture, strain, and traffic data, but they cannot directly observe microscale features throughout a pavement. Digital twins must therefore integrate sparse field measurements with laboratory-derived microstructure models. This integration is a statistical and institutional challenge, not only a technical one. It requires assumptions about representativeness, sampling, and transferability. Transparent treatment of these assumptions is essential if the twin is to support fair and defensible decisions.

4. System Architecture and Computational Trade-Offs

The architecture of a microstructure digital twin can be organized into physical, data, model, and decision layers. The physical layer includes materials, construction processes, pavements, and sensors. The data layer includes imaging, testing, field monitoring, and external datasets such as climate and traffic. The model layer includes image analysis, material models, micromechanical simulations, surrogate models, and lifecycle assessment. The decision layer includes mixture design, quality assurance, maintenance planning, and policy evaluation. The interfaces between these layers determine the system's performance. A poorly designed interface can cause data loss, latency, or misalignment between model outputs and the

decisions they are meant to support. The decision layer is where digital twin outputs must align with agency workflows, contractor practices, and regulatory obligations. A high-fidelity simulation that cannot be interpreted by a pavement engineer or accepted by a specification authority will have limited influence. Conversely, a simplified indicator that is transparent, reproducible, and linked to performance thresholds can be integrated into procurement and quality assurance. The architecture should therefore expose not only predictions but also confidence ranges, assumptions, and sensitivity to input variability. This aligns with broader work on pavement management systems, which have long emphasized the need to connect material condition to investment prioritization [14]. Digital twin architecture for infrastructure must also account for the fact that assets are long-lived and frequently modified through maintenance, overlays, and repairs [15]. The virtual representation must be versioned, auditable, and capable of reconciling discrepancies between design intent and as-built condition.

Computational trade-offs are central to system viability. High-fidelity micromechanical models can require substantial computing resources, especially when many aggregate particles, contact laws, and damage evolution are represented. Cloud computing can provide elasticity, but it introduces dependencies on network availability, data transfer costs, and cybersecurity. Edge computing can reduce latency and preserve local control, but it limits model complexity. A hybrid architecture may be preferable, in which routine screening uses reduced-order surrogates while high-fidelity simulations are reserved for critical design decisions or forensic investigations. This mirrors patterns in aerospace and manufacturing digital twins, where fidelity is allocated according to decision criticality rather than uniformly maximized [16]. In manufacturing, reference architectures have been developed to separate physical, communication, and application layers, enabling modular substitution of models and sensors [17]. Pavement digital twins can learn from these architectures but must adapt them to outdoor, public, and multi-owner environments.

Another trade-off concerns deterministic versus probabilistic modeling. Asphalt microstructure is inherently variable, and performance predictions are uncertain. A deterministic twin that produces a single number may appear precise but can mislead decision-makers. A probabilistic twin can represent uncertainty but may be more difficult to communicate and regulate. The appropriate balance depends on the decision context. For mixture design, probabilistic ranges can help evaluate risk of early failure. For routine acceptance testing, simpler deterministic checks may be sufficient. The architecture should support both modes without forcing unnecessary complexity. This requires careful separation between the core material representation, the computational model, and the decision interface. Standards efforts for digital twins in manufacturing emphasize interoperability and lifecycle management, and similar principles can inform pavement applications [18]. Without such separation, digital twins risk becoming monolithic systems that are difficult to validate, update, or transfer across agencies.

5. Integration with Performance-Oriented Design and Life-Cycle Governance

Performance-oriented pavement design seeks to specify materials and structures based on expected performance rather than prescriptive volumetric or method-based requirements. Digital twin modeling of microstructure can support this shift by providing mechanistic links between material features and distress mechanisms. For example, aggregate angularity and orientation can influence interlock and rutting resistance, while void connectivity can affect moisture damage and freeze-thaw durability. Binder aging and mastic properties can influence

fatigue cracking and relaxation. A digital twin can simulate these relationships and generate performance indicators that are more directly tied to field outcomes than conventional volumetric parameters. However, integration into design practice requires more than technical capability. It requires validation against accelerated pavement testing, field sections, and long-term performance data. It also requires acceptance by agencies, contractors, and material suppliers who may bear different risks and costs.

Life-cycle governance is essential because pavement decisions unfold over decades. A digital twin that only supports initial design misses the majority of lifecycle value. Maintenance, rehabilitation, and reconstruction decisions depend on condition assessment, remaining life estimation, and budget constraints. Microstructure-aware twins can contribute by tracking aging, damage accumulation, and moisture exposure over time. They can also support scenario analysis for different maintenance strategies. Life-cycle assessment methods provide a framework for comparing environmental burdens across materials and processes [19]. Studies of asphalt recycling and alternative materials show that environmental benefits depend on transport distances, plant energy sources, and mixture performance [20]. A digital twin can improve these assessments by linking microstructure to durability and, therefore, to replacement cycles. A mixture that performs poorly at the microscale may require more frequent interventions, undermining apparent environmental savings. Conversely, a durable mixture with higher initial impacts may yield lower life-cycle burdens.

Governance challenges arise when digital twin outputs affect procurement and liability. If a model predicts early failure, who is responsible, and what recourse exists? If a model recommends a maintenance delay, how are risks distributed between agency and contractor? These questions are not resolved by better simulation alone. They require contractual mechanisms, data sharing agreements, and transparent model validation. Governance must also address data ownership. Contractors may collect construction data, suppliers may hold proprietary mix designs, and agencies may operate monitoring networks. A digital twin that aggregates these data creates value but also raises questions about control and benefit sharing. Federated governance models, in which data remain with owners but derived insights are shared, may offer a middle path. Such models require technical standards for secure computation and institutional rules for dispute resolution. Without them, digital twins may reinforce existing power asymmetries rather than democratize performance knowledge.

6. Deployment, Robustness, and Fairness

Deployment of microstructure digital twins will occur unevenly across regions and organizations. Large agencies and well-resourced contractors may adopt advanced imaging, simulation, and data analytics, while smaller entities may lack capital, expertise, or personnel. This uneven adoption can create fairness concerns. If performance-oriented specifications depend on digital twin capabilities, smaller suppliers may be disadvantaged. If agencies use digital twins to prioritize maintenance, regions with less data may receive less investment. Addressing these concerns requires deliberate capacity-building, shared infrastructure, and tiered adoption pathways. Public agencies can provide reference models, open datasets, and training. Regional laboratories can offer imaging and testing services. Procurement rules can allow alternative compliance pathways for organizations that lack advanced capabilities. The goal should be to raise the floor of performance knowledge, not to create a technological divide.

Robustness is another deployment imperative. Digital twins must operate under sensor failures, missing data, communication outages, and model drift. Asphalt pavements are

exposed to extreme weather, heavy traffic, and unexpected events. A twin that fails silently or produces erratic recommendations can erode trust. Robust design includes redundancy in sensing, fallback to simpler models, and continuous monitoring of prediction errors. It also includes cybersecurity. Infrastructure data can be sensitive, and model manipulation could lead to unsafe maintenance decisions. Security must be designed into data pipelines, model updates, and access control. Robustness also involves validation across diverse climates and material sources. A model trained on one region may not transfer to another because aggregate geology, binder chemistry, and construction practices differ. Transfer learning and domain adaptation can help, but they require ongoing data collection and feedback. Deployment should therefore be treated as a learning process rather than a one-time installation.

Fairness also concerns the distribution of environmental and health burdens. Pavement construction and maintenance affect air quality, noise, and local economies. Digital twins can optimize for cost and performance but may overlook distributional impacts. For example, a strategy that minimizes agency cost might shift traffic to vulnerable communities or increase plant emissions near disadvantaged areas. A performance-oriented digital twin should include equity indicators alongside engineering and environmental metrics. This requires interdisciplinary collaboration with planners, environmental justice researchers, and community stakeholders. It also requires transparency about trade-offs. No model can optimize all objectives simultaneously. The twin can, however, make trade-offs explicit and support deliberative decision-making. In this sense, the digital twin is not a neutral calculator but a boundary object that mediates between technical and political domains.

7. Sustainability and Circular Material Use

Sustainability in pavement engineering increasingly involves recycled materials, warm-mix technologies, and alternative binders. Reclaimed asphalt pavement, recycled asphalt shingles, crumb rubber, and bio-binders introduce heterogeneity that complicates performance prediction. A microstructure digital twin can help characterize how these materials distribute within the mixture and how they affect damage mechanisms. For example, aged binder from reclaimed asphalt may blend incompletely with virgin binder, creating stiff zones that influence cracking. Digital twins can model blending and identify mixture designs that balance recycled content with durability. This supports circular economy goals without sacrificing performance. Life-cycle assessment can then evaluate whether increased recycling reduces net environmental impact when transport, processing, and longevity are considered [19]. The twin can provide the performance data needed to make such assessments more reliable.

However, sustainability claims must be treated cautiously. A digital twin can be used to justify a particular material strategy, but it can also obscure uncertainties. If model inputs are biased toward available data, less-studied materials may be unfairly penalized. If environmental metrics omit key impacts, decisions may shift burdens rather than reduce them. Governance should therefore require transparency in model boundaries, data sources, and assumptions. Independent validation and multi-stakeholder review can help. The twin should also support adaptive management, allowing strategies to be revised as new data emerge. Sustainability is not a fixed property of a mixture but an outcome of decisions across extraction, production, construction, use, and end-of-life. Digital twins can improve those decisions only if they are embedded in institutions that value long-term and distributional outcomes.

8. Policy, Standards, and Institutional Implications

Policy frameworks will shape whether digital twin modeling of asphalt microstructures becomes a widespread practice or remains a research specialty. Standards are needed for data formats, imaging protocols, model validation, and uncertainty reporting. Without standards, agencies cannot compare models or accept digital twin outputs in specifications. International standards for digital twins in manufacturing offer a starting point, but pavement-specific standards must address material variability, field validation, and lifecycle governance [18]. Certification of models and modelers may also be necessary. Just as testing laboratories are accredited, digital twin providers may need to demonstrate competence, transparency, and reproducibility. Certification should not become a barrier to innovation, however. Tiered certification could allow simpler models for routine use and more complex models for critical decisions.

Procurement policy is another lever. Agencies can require digital twin deliverables for major projects, but they must also invest in the capacity to review and use them. Contracting mechanisms should clarify data rights, model ownership, and liability. Performance-based contracts can reward durability and environmental outcomes, but they require reliable measurement. Digital twins can support measurement but cannot replace field verification. Policies should also encourage data sharing while protecting proprietary information. Public funding for open datasets and reference models can reduce duplication and accelerate learning. Regional collaboration can help smaller agencies pool resources. National and international coordination can harmonize standards and promote interoperability. The policy challenge is to create an ecosystem in which digital twins improve public outcomes without entrenching monopolies or exacerbating inequities.

9. Research Roadmap and Future Directions

Future research should address several interconnected priorities. First, microstructure characterization must become more efficient and standardized. Imaging, segmentation, and feature extraction should be validated across laboratories and material types. Second, multiscale modeling must better connect microscale mechanisms to pavement-scale performance. This requires advances in homogenization, damage mechanics, and uncertainty quantification. Third, data architectures must support secure, federated, and interoperable data exchange. Fourth, human factors and decision science must be integrated so that digital twin outputs are usable and trustworthy. Fifth, lifecycle and equity metrics must be embedded in model evaluation. Sixth, field validation must be expanded through instrumented pavement sections and long-term monitoring. Seventh, governance research must examine how contracts, standards, and regulations shape adoption and outcomes. These priorities are not sequential; they must advance in parallel.

A research roadmap should also include demonstration projects that test digital twins in real procurement and maintenance contexts. Such projects can reveal institutional barriers that laboratory studies miss. They can also build trust among stakeholders. Demonstration projects should include diverse agencies, contractors, and communities. They should report both successes and failures. Negative results are valuable for understanding limits. Finally, education and workforce development are essential. Pavement engineers, data scientists, and policymakers need shared literacy in digital twin concepts, limitations, and ethics. Interdisciplinary curricula and professional training can bridge disciplinary divides. Without a skilled workforce, digital twins will remain tools of a few experts rather than infrastructure for collective decision-making.

Conclusion

Digital twin modeling of asphalt mixture microstructures offers a promising pathway toward performance-oriented pavement design, but its success depends on system-level design rather than technical sophistication alone. This paper has argued that digital twins should be understood as socio-technical infrastructures that link imaging, sensing, simulation, machine learning, lifecycle assessment, and governance. The microscale features of asphalt mixtures, including aggregate morphology, void structure, mastic distribution, and aging, can be represented in virtual models that update with field data. These models can support mixture design, quality assurance, maintenance planning, and policy evaluation. However, they also introduce trade-offs involving fidelity, latency, cost, scalability, uncertainty, and robustness. They raise questions about data ownership, liability, fairness, and sustainability. Addressing these questions requires standards, procurement reform, capacity-building, and interdisciplinary research. The required reference on coarse aggregate morphology and image recognition illustrates the kind of empirical foundation needed, but it must be integrated into broader architectures and institutions. A digital twin that is accurate but opaque, powerful but inequitable, or innovative but ungovernable will not fulfill its promise. The next generation of pavement design should therefore pursue not only better models but also better systems of knowledge production and decision-making. If designed with care, digital twins can help pavements endure longer, consume fewer resources, and serve communities more equitably.

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