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16. Abstract

Transportation infrastructure construction and maintenance consume energy and finite resources, and have substantial environmental impacts, primarily from the manufacturing of cement, concrete, asphalt, and steel. New feedstock materials and technologies for producing these materials can result in lower life cycle costs, use of local materials, creation of local employment, and reduced environmental impacts. These goals point to the urgent need for adopting innovative alternatives. However, implementation requires confidence on the part of materials producers, contractors, and infrastructure owners that the new materials and technologies can achieve these goals. Implementation demands rigorous testing, risk management, and stakeholder confidence in the engineering performance, environmental benefits, and economic viability of new materials and technologies. This report introduces a structured evaluation framework, "Lab2Slab2Practice," aimed at accelerating the adoption of these new materials and technologies. Key strategies include leveraging social- behavioral-change models, such as the Unified Theory of Acceptance and Use of Technology and Kotter's 8-Step Change Model, to mitigate risks and facilitate adoption. A comprehensive review of prior successful government programs and initiatives, including AASHTO's Superpave and Pavement Mechanistic-Empirical Design tools, underscores the importance of interagency collaboration and support, rapid experimentation, theoretical simulations, and engagement by owners (primarily departments of transportation), contractors, and other stakeholders. Regional centers are proposed as clearinghouses to systematically evaluate materials across Technology Readiness Levels, emphasizing engineering performance, scalability, and constructability. Public-private coalitions are proposed to fund these centers, ensuring transparent dissemination of findings and stakeholder training. With sufficient resources and alignment of federal, state and industry support, the framework targets reducing material adoption timelines from over a decade to 5 years or less, moving materials from ideas to use in standard practices, and improving cost-effectiveness and environmental benefits.

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Research Report

April 2025

Lab2Slab2Practice

A Framework for a Faster Implementation of Innovative Concrete Materials and Technology

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Lab2Slab2Practice: A Framework for a Faster Implementation of Innovative Concrete Materials and Technology

A National Center for Sustainable Transportation Research Report

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Lab2Slab2Practice: A Framework for a Faster Implementation of Innovative Concrete Materials and Technology

Executive Summary

The materials used for construction, rehabilitation, and maintenance of transportation infrastructure are significant contributors to energy consumption, finite resource use, and environmental impacts, particularly from the production of materials like cement, concrete, asphalt, and steel, as well as several key construction processes for their installation. In addition, these materials often have feedstock material supply chains that are subject to international cost volatility, and that may not be structured to achieve maximum cost-effectiveness and creation of local employment. Identification and implementation support for new American sourced materials. These new materials may be scaled nationally or make use of regionally available feedstocks (minerals, recycled materials from industrial waste, and agricultural and forest waste biomass as examples), both of which will help insulate transportation projects across the country from international materials cost volatility, particularly for cement, asphalt and supplementary cementitious materials which have significant imported content.

The energy use and negative environmental impacts of concrete mainly come from cement production, which is its major binding element. The United States (U.S.) cement sector contributes 61% of the annual stack output of the minerals subsector (cement, lime, glass, and soda ash) contributing to changes in regional weather and 1.7% of total U.S. contributions to those effects, as well as other environmental impacts. In the global context, cement accounts for approximately 7% of the outputs contributing to global and regional weather changes. A vast majority of outputs from cement production contributing to weather change come from the decarbonation of limestone (i.e., calcining) to produce clinker and burning fossil fuels to heat the kiln to the high required temperatures.

The shift to alternative materials to achieve cost-efficiency, robust supply chains, growth of local employment, and environmental goals must consider public safety based on engineering performance, constructability, and the scalability of material supply chains. New materials must undergo rigorous testing and stepwise validation to build confidence that they meet engineering performance standards, reduce lifecycle environmental impacts, and are economically viable for widespread use. Such rigorous stepwise evaluation will help stakeholders identify risks associated with the use of new materials and develop risk management strategies until the material is integrated into standard practice.

Social behavioral change models, traditionally applied in fields such as information technology (IT), business, education, and public health, explain how a new technology diffuses across different population groups. For instance, according to the Diffusion of Innovations (DOI) model, implementation starts with early adopters with a higher level of risk tolerance, but support for effective risk management is necessary to bridge the adoption gap for the next set of adopters. The Unified Theory of Acceptance and Use of Technology (UTAUT) model is helpful for analyzing stakeholder risks, emphasizing the need to reduce risks that impact both individual's and organizations' job performance and meet performance expectancies. It also emphasizes minimizing user efforts while leveraging social influence and facilitating conditions. Kotter's 8-Step Change Model provides a structured framework for achieving organizational and institutional change. We summarize linkages between these approaches and the proposed pathway to support new materials adoption. This report also underscores the concept of the Valley of Death (VoD), a critical stage where support for innovators is vital, especially in securing funding to scale up production from bench scale to pilot plants. A review of past and ongoing inter-agency and other government programs and transportation agency initiatives for implementation is provided in this report to help identify possible strategies to overcome VoD. The reviewed programs include the Accelerated Innovation Deployment - Pilot Program (AID-PT), the implementation of Superpave and AASHTOWare PavementME design tool by the American Association of State Highway and Transportation Officials (AASHTO), and the Materials Genome Initiative. The review highlights the importance of rapid experimentation, modeling simulations, accelerated life cycle testing, open access data, and states' Departments of Transportation (DOT) involvement.

Overall, the review of implementation challenges and strategies highlights the critical need for credible regional centers as clearinghouses that systematically evaluate innovative materials through a step-by-step assessment framework referred to here as "Lab2Slab2Practice". Following this model, these centers will ensure rigorous assessment and thorough testing of engineering performance, environmental and economic viability, scalability, and constructability, addressing a critical gap in the movement of innovative materials from concept and bench scale to full market penetration and integration into standard practice. These centers would apply a structured risk assessment framework to accelerate the adoption of alternative types of concrete in standard construction practices. Identification and communication of supply chain constraints on development and implementation of innovative materials facing industry, such as permitting.

Funded through public-private coalitions, the centers will rigorously evaluate technologies across various Technology Readiness Levels (TRL), from prototyping to commercialization, while placing a significant emphasis on risk management by addressing uncertainties around safety, engineering performance, environmental impact, scalability, and constructability. This structured approach advances the technology from the Lab scale (TRL 3-4, bench-scale production) to the Lab2Slab scale (TRL 5-6, pilot production at about 1-2 tons), then to the Slab2Pilot scale (TRL 7-8, 10s to 100s of tons), and ultimately from Pilot2Practice (TRL 9 full commercialization).

At each scale, performance data must be made publicly accessible through technical reports, databases, webinars, and conference presentations to ensure comprehensive, transparent, and standardized communication of findings with a broad range of stakeholders across the value chain. This approach enables the identification of viable technologies and filtering out unviable ones with unsupported claims, facilitating adoption among broader stakeholders across the sector.

The centers must focus on bridging the adoption gap by reducing efforts from implementers through targeted training and developing tools customized for key stakeholders, including ready mix concrete producers, implementers (government and private owners), and specifiers (engineers and architects). The technical reports and peer-reviewed publications from the centers will support stakeholders in integrating the new technologies into state DOT specifications, building codes, guidance, and other standards, establishing new concrete materials as mainstream construction materials.

The centers need to be supported with sufficient resources for high throughput experimentation and comprehensive assessment. This requires sufficiently large facilities with industrial-scale equipment and infrastructure to match the flow of new materials coming into the assessment pipeline. The funding for such centers requires intra-governmental agency coalitions. Additionally, to transition from Slab2Pilot scale to Pilot2Practice, alignment of federal support with state DOTs is a must and needs to occur in the form of funding and grants for pilot projects, laboratory equipment, training, and human resources, as was seen in past programs such as Superpave and AASHTOWare Pavement Mechanistic-Empirical (ME) design implementation so that the states can continue to make progress and transition the new materials into their standard of practice.

The goal of the framework is to reduce the typical timeline for adoption from over 10 years to a target of 5 years, embedding concrete with reduced environmental impacts, greater cost-efficiency, and more robust regional supply chains into standard practice and resulting in continual improvements in concrete technologies used in infrastructure projects.

1. Introduction

The materials used for construction, rehabilitation, and maintenance of transportation infrastructure are significant contributors to energy consumption, finite resource use, and environmental impacts, particularly from the production of materials like cement, concrete, asphalt, and steel, as well as several key construction processes for their installation. In addition, these materials often have feedstock material supply chains that are subject to international cost volatility, and that may not be structured to achieve maximum cost-effectiveness and creation of local employment. Identification and implementation support for new American sourced materials. These new materials may be scaled nationally or make use of regionally available feedstocks (minerals, recycled materials from industrial waste, and agricultural and forest waste biomass as examples), both of which will help insulate transportation projects across the country from international materials cost volatility, particularly for cement[1], asphalt[2] and supplementary cementitious materials[3] which have significant imported content.

Although a comprehensive benchmarking of national transportation infrastructure environmental impacts, which spans the industry, energy, and transportation sectors, has not yet been completed, there are examples of the scale. The energy use and negative environmental impacts of concrete mainly come from cement production, which is its major binding element. The United States (U.S.) cement sector contributes 61% of the annual stack output of the minerals subsector (cement, lime, glass, and soda ash) contributing to changes in regional weather and 1.7% of total U.S. contributions to those effects *(U.S. Environmental Protection Agency, 2021)*, as well as other environmental impacts. In the global context, cement accounts for approximately 7% of the outputs contributing to global and regional weather changes *(Miller et al., 2021)*. A vast majority of outputs from cement production contributing to weather change come from the decarbonation of limestone (i.e., calcining) to produce clinker, the primary material of portland cement, and burning fossil fuels cement plants to provide the high temperatures required to decarbonize limestone and manufacture clinker (with kilns operating at 1,350C to 1,400C) *(Miller et al., 2024)*. The overall environmental impacts of cement production are predominantly driven by the enormous demand for cement-based materials. Over 4 billion metric tons of cement is consumed annually worldwide *(Hatfield, 2022)*.

Other transportation infrastructure materials have notable environmental impacts from production as well, such as asphalt binder used to make asphalt concrete, and steel. Asphalt and steel, like concrete, also have significant environmental impacts

[1] https://concretefinancialinsights.com/us-cement-industry-data ;
[2] https://www.asphaltpavement.org/uploads/documents/Buy_America_Impacts_on_Asphalt.pdf
[3] https://www.volza.com/p/fly-ash/import/import-in-united-states/

Innovation in transportation infrastructure materials is needed to achieve greater cost-efficiency, robust supply chains, growth of local employment, and environmental goals. The implementation of alternative materials must consider public safety based on engineering performance, constructability, and the scalability of material supply chains.

Implementation of new materials requires sufficient assessment and mitigation of risks to public safety, cost-efficient use of limited infrastructure funding, and the most efficient use of other valuable resources such as time and availability of raw materials. New materials that do not meet engineering performance requirements put public safety at risk and require more frequent maintenance, rehabilitation, and replacement, which produce additional costs and environmental impacts over the life cycle. New materials should undergo thorough analysis to build assurance that they meet engineering performance requirements, truly reduce environmental impacts over the life cycle, have scalable supply chains to meet at least regional demands, are constructible, and are resource-effective enough for large-scale implementation. Screening for this information is essential to build the confidence needed for widespread adoption of new materials that meet the demands for engineering performance, cost-effectiveness, and reduced environmental impacts.

Currently, the typical time to move a new material or technology to full-scale widespread implementation is 10 years or more. A much faster pace of data-driven confidence-building is needed federal, state, and local transportation infrastructure agencies to confidently move forward with implementation, and to support the materials and construction industries in creating a pipeline of new materials moving from conceptual ideas to standard practice. Identification and communication of supply chain constraints on development and implementation of innovative materials facing industry, such as permitting.

The scope of this report encompasses the development of a strategic framework to accelerate the adoption of new types of concrete in construction, reducing the time from initial concept to full-scale implementation. The report integrates knowledge from key models such as the Diffusion of Innovations (DOI), Technology Acceptance Model (TAM), Unified Theory of Acceptance and Use of Technology (UTAUT), and Kotter's 8-Step Change Model, as well as decades of the authors' experience moving innovation to implementation in the materials and construction industry, to create a holistic approach. It outlines the technical, environmental, scaling constraints, and regulatory assessments necessary for moving new types of concrete from laboratory testing to pilot projects and eventual mainstream use. Additionally, the framework addresses the role of engineers, architects, industry stakeholders, and regulatory bodies in overcoming barriers to adoption while performing due diligence, focusing on reducing effort expectancy, and ensuring long-term sustainability. The report also identifies critical funding stages and evaluates the technology's performance through Technology Readiness Levels (TRL), with the goal of institutionalizing new materials meeting cost, robust supply chain, economic development, and environmental goals within standard design and construction practices.

The proposed process is called “Lab2Slab2Practice” and includes the steps needed for benchmarking, feedback, and confidence building to produce a fast-moving pipeline of new materials in a manner that maximizes the value of public and private investment while efficiently leveraging the current workforce. The process is designed to create centers of excellence that can be replicable in regions across the U.S.

2. Review of Behavioral Models for Technology Adoption

2.1 Chapter Overview

Over the years, several theoretical models have been developed to explain behavioral changes in new technology adoption, with a marked increase in research and experimentation in the second half of the 1990s *(Al-Suqri and Al-Aufi, 2015)*. These models aim to explain the life cycle of the adoption of new technologies by certain populations or user groups and identify steps for removing roadblocks to their success. While most of these models originate from social science and behavioral change disciplines, they have been widely applied in rapidly evolving sectors such as information and communication technology, as well as in education, public health, business, and many other fields.

These models are summarized in this chapter to provide potential insights into understanding the design and construction sector's needs for adopting innovative materials. Although their applicability varies depending on the specific context and field, the core principles and guidelines remain relevant for advancing the adoption of new concrete materials and practices in design and construction. The focus of this summary will be on demonstrating how these concepts can be leveraged to drive innovation in concrete materials, ultimately accelerating the adoption and implementation of emerging alternative materials and practices within the construction industry.

2.2 The Diffusion of Innovation Theory (DOI)

The DOI Theory is one of the earliest social science theories developed by sociologist Everett Rogers in 1962 *(LaMorte, 2022)*, and it explains how new ideas, products, or innovations spread (diffuse) across a social system over time. According to DOI theory, the key to adoption lies in the individual's perception of the idea, behavior, or product as new and innovative. This perception is essential, as it enables the diffusion process to occur. Without a sense of novelty or innovation, adoption is unlikely to take place *(LaMorte, 2022)*.

The main components of the DOI theory are innovation characteristics, adopter categories, communication channels, social systems, external influencers, and barriers to diffusion. Each of these components will be discussed below, and their application to concrete sustainability will be discussed accordingly.

The five factors affecting adoption, according to Rogers *(Rogers, 2003)*, are relative advantage, compatibility, complexity, trialability, and observability. Applying these factors to new and emerging materials (cements, supplementary cementitious materials (SCMs), fibers, etc.) in the concrete space could be as follows:

- Relative Advantage: New cements or SCMs must offer clear benefits over traditional Portland cement, and the new SCMs typically must provide similar performance as the traditional SCMs: coal fly ash and blast furnace slag. These advantages are not limited to technological performance and could include lower environmental impacts, improved performance in certain conditions, and initial or life cycle cost savings.
- Compatibility: New cements and SCMs need to align with current construction practices, existing materials, and industry standards. Compatibility with existing production facilities and ease of use for producers and contractors is critical.
- Complexity: The more complex the use or production process of the new cements, the slower their adoption is likely to be. Simplifying the application or training users will effectively accelerate diffusion.
- Trialability: Project owners, such as the government and private owners, must have opportunities to test the new materials in demonstration projects to reduce perceived risk. Demonstration projects and pilot projects will be necessary to give stakeholders confidence in the material and to elucidate any changes in performance that might not be measurable in a laboratory setting.
- Observability: Successful projects using new cements need to be highly visible within the industry and practice. Case studies, public infrastructure projects, and data showcasing benefits can help make the advantages more observable to potential adopters.

Rogers *(Rogers, 2003)* classifies the adopters of a technology into the following classes. The position of each of these groups and the size of each group are illustrated in Figure 1 with respect to the technology adoption life cycle. The main general attitudes toward a new technology can be classified as follows:

- Innovators (Techies): 2.5% of the group to adopt the innovation. This group adopts early because they enjoy experimenting and troubleshooting.
- Early Adopters (Visionaries): 13.5% of the group see value in the technology's potential, even if it is not fully refined.
- The Early Majority (Pragmatists): 34% of the group who adopt when the technology proves useful and reliable, avoiding technologies with glitches.
- The Late Majority (Conservatives): 34% of the group will adopt it when it is necessary and well-proven by peers, favoring stability over innovation.
- Laggards (Skeptics): 16% of the group often resist technology, contributing by preserving older skills or promoting ethical debates.

The "chasm" is the gap between early adopters who embrace innovation and the majority who require proven reliability. Moving a technology across this chasm is crucial for widespread adoption, often achieved by creating a minimum viable product that meets the needs of pragmatists in real-world conditions. Success in new technology adoption can often be linked to bridging this divide; for example, efforts in Silicon Valley often specialize in helping technologies cross this gap through agile development, bringing together interdisciplinary teams to refine products *(Burbank, 2022)*.

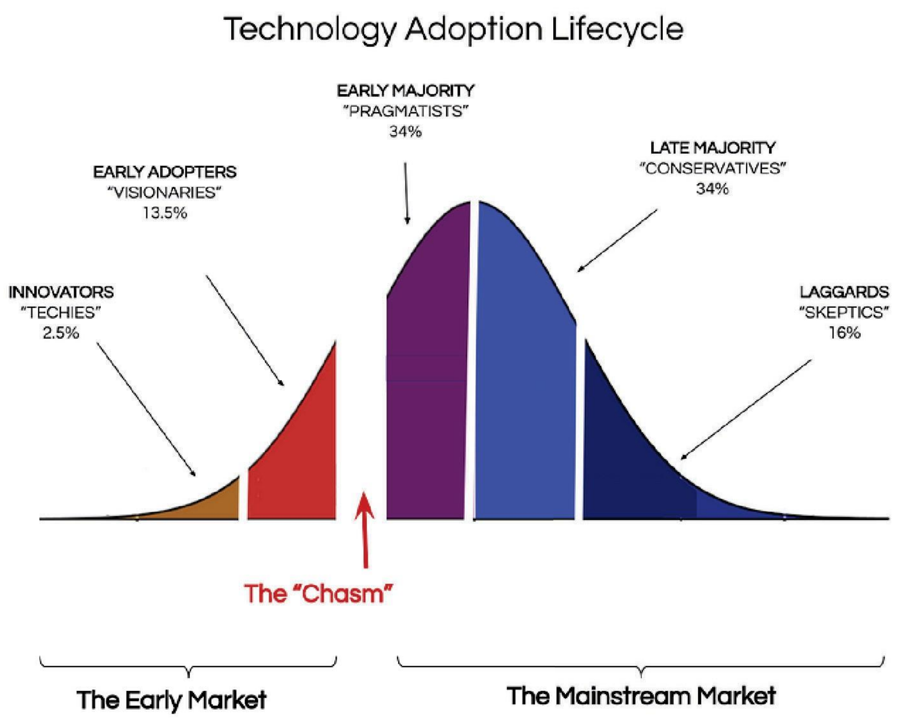

Figure 1. The life cycle of technology adoption from reference (*9*) adopted from reference (*10*).

The five groups of adopters in the sustainable concrete context can be defined as follows:

- Innovators: Large construction firms or those developing high-profile projects that prioritize sustainability might be early adopters willing to experiment with innovative concrete.
- Early Adopters: Architects and engineers working on cutting-edge or green projects may push for new materials. Governments with procurement regulations or incentives for reducing environmental impacts, such as permit prioritization for projects with LEED certificates, can motivate this group.
- Early Majority: More risk-averse companies might adopt these materials after seeing several successful implementations.
- Late Majority: State and federal governments that prefer to maintain well-established methods may only adopt innovative concrete mixtures once they become a standard in the industry.

- Laggards: This group will likely adopt innovative concrete only when they become the default material, either due to regulatory pressures or industry standards.

Another important factor identified in the DOI theory is the communication channels. This factor is particularly critical for the adoption of new materials or practices in construction. The performance data from demonstration projects, high-profile pilot projects, training, and other communication targeted for producers, contractors, and specifiers could be disseminated through:

- Peer-to-peer communication
- Industry trade associations (national and regional chapters)
- Industry conferences (regional and national)
- Professional organizations, such as the American Concrete Institute (ACI), American Association of State Highway and Transportation Officials (AASHTO), ASTM International, the National Ready Mix Concrete Association (NRMCA), and their regional chapters.

Another factor accelerating the adoption of technology, according to DOI theory, is the external influencers. These could include:

- Local, state, federal, and global mandates, targets, goals, regulations, and policies
- Financial incentives such as grants, tax credits, and increased tariffs on imported goods
- Public pressure and desires to be viewed favorably by reducing environmental impacts; notably, this pressure can come through an organization with company environmental targets, trickling down to all aspects of operation, including materials procurement.

The DOI theory also acknowledges the barriers to adoption and strategies to overcome the barriers. Key barriers to adopting new concrete mixtures in the U.S. include, but are not limited to:

- Economic concerns: The cost of materials produced locally or in a different method or raw materials than traditional cementitious materials may be higher than fly ash from other states and blast furnace slag imported from Asia and Mexico, currently primarily imported to improve concrete durability but also in some locations to meet environmental goals.
- Permitting and regulatory constraints: Obtaining the various permits and environmental assessment studies required for scale production involves significant time and investments, and the permitting process can be especially lengthy and have large uncertainty of success in some states. Although, appropriate permitting is a key pathway to ensuring limited deterioration of the environment and human health in neighboring areas the process could be streamlined and bottlenecks removed to facilitate faster material production while still ensuring the

operation meets the environmental and safety requirements. Depending on the operations, permits can cover a wide range of air and water quality, environmental review, mining, reclamation, and others.

- Supply chain, logistics, and material availability: A supplier or distributor might not be available regionally, some raw materials may not be available locally, and transportation by rail or truck might not already be in place.
- Incompatibility with existing construction practices: higher water demand and adverse effects on workability, finishability, color and other aesthetics, bleed water, incompatibility with current admixtures, drying shrinkage, and the rate of strength gain could be perceived as challenges.
- Lack of engineering performance and environmental impact data: Small amounts of engineering performance data, insufficient demonstration, and a lack of life cycle assessment results pose challenges to innovators and implementers. Less-tested materials are often associated with high risks and are more difficult to adopt.
- Lack of standard specifications: Materials or technologies outside existing standard specifications carry unquantified risks and face more implementation challenges, such as difficulty easily including them in projects than those with established standards.

2.3 Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT)

TAM was specifically developed by Davis in 1985 *(Davis, 1989, 1985)* to understand how users come to accept and use a technology particularly focused on information technology. Since its development, TAM has been widely used and become a key model in understanding human behavior in accepting or rejecting a technology. According to TAM, two main factors influence adoption:

- Perceived usefulness: The degree to which a person believes the technology will enhance their job or task performance.
- Perceived ease of use: The degree to which a person believes the technology is easy to use.

According to Davis *(Davis, 1989, 1985)* perceived usefulness refers to the extent to which an individual believes that using a particular system will improve their job performance. Meanwhile, perceived ease of use is defined as the degree to which an individual believes that using the system will be effortless. These two factors play a critical role in determining the likelihood of adopting new technologies. Both criteria were hypothesized to be directly influenced by the system design characteristics (represented by X1, X2, and X3 in Figure 2) (Marangunić and Granić, 2015), and an expansion of this representation is shown in Figure 3.

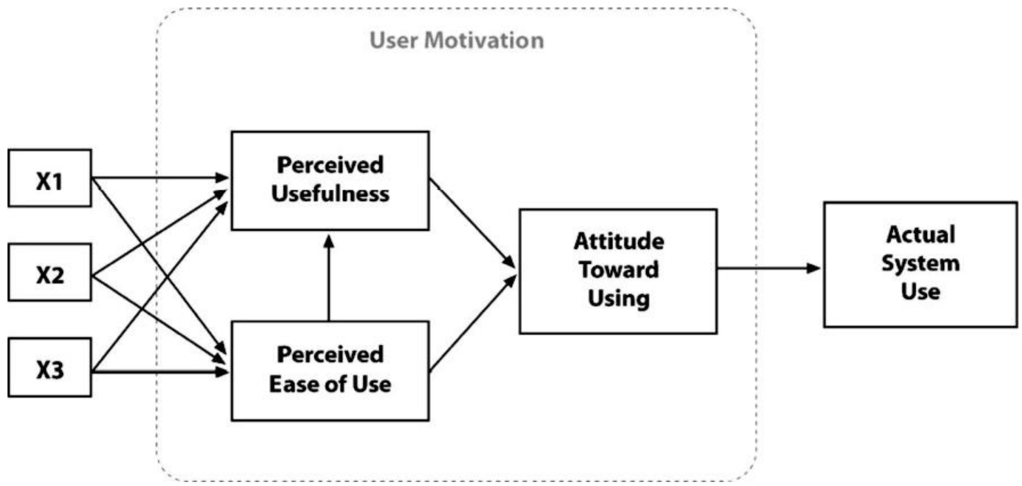

Figure 2. Technology acceptance model (*12*).

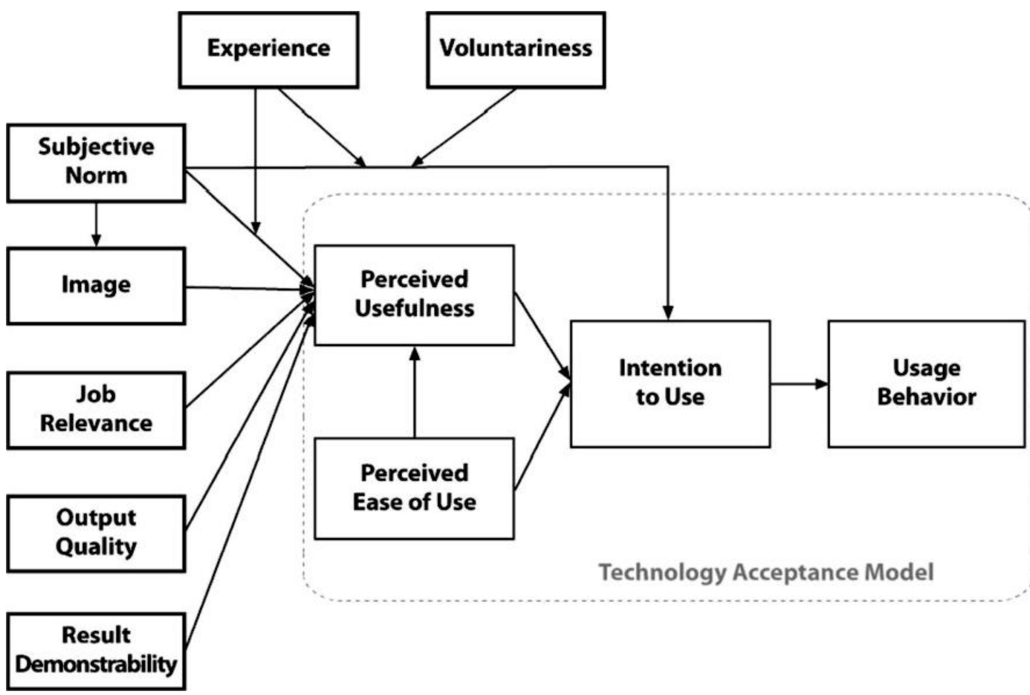

Figure 3. An extension of TAM in a later study (*14*).

Later, the Unified Theory of Acceptance and Use of Technology (UTAUT) was developed *(Venkatesh et al., 2003)*, which builds on TAM and includes additional factors such as social influence and facilitating conditions (like infrastructure) to better predict technology adoption. UTAUT has often been used in organizational and educational settings to understand how technologies are accepted by groups *(Venkatesh et al., 2003)*. The theory includes four main factors as essential in the adoption of technology:

1. Performance expectancy: The perceived benefits of using innovation to improve the individual's performance in their job.
2. Effort expectancy: The perceived ease of using the innovation.
3. Social influence: How much others' opinions affect adoption.
4. Facilitating conditions: External factors like support systems and resources.

Engineers and practitioners need to be confident that using innovative concrete will not compromise project performance, or put their reputation at risk, or adversely affect their job performance. If risks to engineering performance or compliance with standard practices are high, the innovation might hinder job performance rather than improve it, making adoption less attractive. There is a real concern that any material failure (cracking or different aesthetics) could result in consequences severe enough to endanger an individual's professional license, retention, or promotion or result in litigation for the organization as well as significant loss of revenue if the construction is rejected due to failure or different looks or performance compared to traditional materials. Assuring users that innovative concrete meets industry standards (e.g., ASTM or ACI) and performance expectations are clearly outlined in the project owner's specifications is essential to reduce perceived risks and increase the likelihood of adoption. Advanced knowledge of constructability and aesthetics of the finished product by the user and communication to the client to avoid adverse reactions to surprises.

Effort expectancy is how easy stakeholders (individuals and organizations) perceive it to be to adopt the new materials in construction. Technologies requiring minimal training are generally perceived as "lower effort" by stakeholders. Offering ongoing and accessible training videos, guide documents, user manuals, certification courses, and other resources can ease the transition and accelerate the learning process. These efforts reduce efforts on the individuals and help the change spread across the organization and integrate into standard practice so that use becomes "normal" or "standard" and does not require a special effort.

Examples below show how user efforts can be reduced for ready mix producers and concrete placers:

- Each material, depending on its properties, will have different impacts on workability, bleed water, setting time, and strength gain; materials that do not change the status quota in terms of workability, slump retention, bleed water, and setting time will be perceived as easier to adopt. Changes in these characteristics will lead to changes in practices, such as curing practices, employing more admixtures or different admixture types (for example, lignosulfonate vs. carboxylate plasticizers), and different types of air entrainer admixture. Setting time is critical and affects the time available for delivery, placement, and finishing as well as the time of saw cutting the joints and from removal. Fast-setting materials may require retarders, or slow-setting accelerators may be needed to saw cut joints or move forms, higher or lower bleed water impacts risks of plastic shrinkage, finishability, and curing process and timing. If the material leads to higher drying shrinkage, reducing admixtures may be needed, which can drive changes in the cost. Any of these changes in practice can be perceived as an increased effort to adopt the material. Education and training are essential for practitioners to adopt new materials faster.

- Practitioners will need support (staff, equipment, supplies, and other resources) to develop and test new concrete mix designs, determine their properties, and customize them using their aggregates and admixtures.

Social influence is the degree to which stakeholders, mainly implementing organizations, perceive that important others believe they should use the technology. Implementers (individuals and organizations) weigh the opinions of respected peers or industry leaders regarding the risks associated with an innovation. Positive social influence, especially from trusted colleagues or organizations, can help mitigate perceived risks and ease the path to acceptance. The entities that are perceived as important in the construction sector may include:

- State and local governments
- High-profile clients or firms
- Legislative offices, local congressional representatives, the mayor's office
- Industry associations
- Federal agencies, FHWA
- Community groups and advocacy organizations concerned with local development and sustainability

Finally, the facilitating conditions are to the level at which individuals believe the organizational and technical support and infrastructure exist to support the adoption of the technology. For the construction sector, these support systems and infrastructure could include:

- Availability of resources: access to new materials and a reliable supply chain
- Technical support, training videos, courses, and workshops
- Performance data and demonstration projects
- Standard specifications
- Design tools
- Test methods
- Certification support: streamline processes to certify new materials or projects to apply for grants, funding, tax credits, etc.
- Cost support, such as incentives, grants, tax credits, etc.

2.4 Kotter's 8-Step Change Model

This model, developed by Kotter in 1995 *(Bedard, n.d.)*, is focused on leading organizational change and outlines eight steps for successfully implementing change, as shown in Figure 4. These steps include creating urgency, forming a powerful coalition, creating a vision, communicating the vision, removing obstacles, creating short-term wins, building on the change, and anchoring the changes in corporate culture.

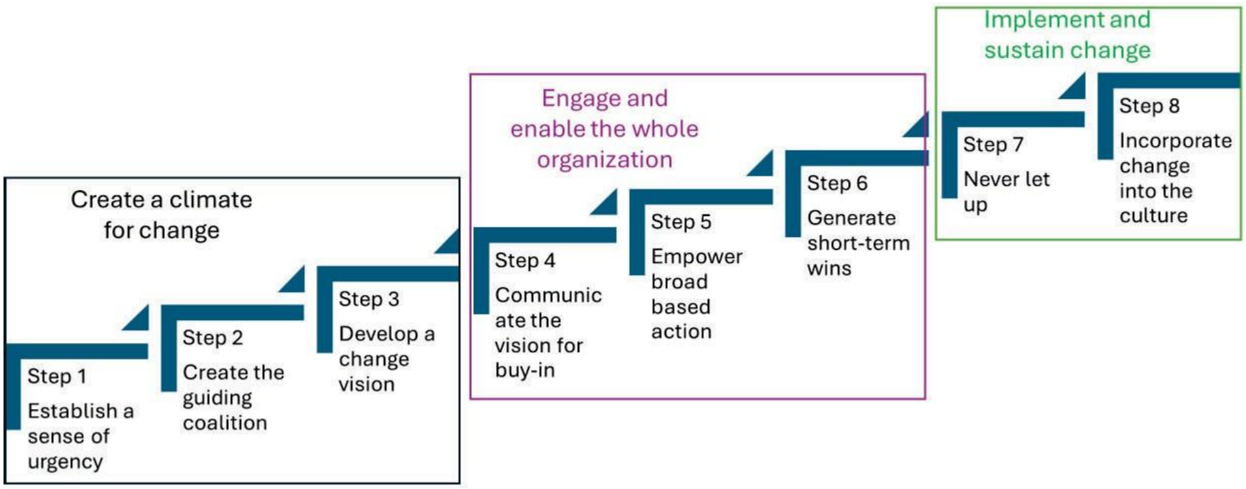

Figure 4. The 8 steps in Kotter's 8-Step Change Model.

The first step in Kotter's model emphasizes the need to develop a sense of urgency around the change. The following actions can be used to build a sense of urgency in the innovative concrete adoption field, several of which are already at play to different degrees across the U.S. and globally.

- Regulatory and market pressures: Emphasize tightening restrictions and tariffs on imported materials, regulations around environmental impacts, government mandates for consideration of environmental impacts in procurement, needs for local economic development, changes in energy markets and the potential for use of co-products from new forms of energy production.
- Demonstrate financial risks: Demonstrate how failing to consider these regulatory and market pressures could lead to financial penalties, loss of market share, or reputational damage as competitors move toward alternative solutions.
- Communicate the crisis: Build urgency by emphasizing the role of construction in economic development and environmental impacts. Highlight the need for action to reduce the industry's environmental impacts through use of innovative materials. Many industry associations and other entities have already been focused on developing roadmaps and communicating the urgency for change to reduce environmental impacts.

- Social Costs of Inaction: Emphasize the long-term economic and societal costs of lack of consideration of robust supply chains, local economic development, and environmental impacts, including economic losses, safety and health impacts, environmental degradation, and social dissatisfaction. Quantifying these costs can illustrate the broader financial and societal implications of inaction, helping stakeholders recognize the value of adopting innovative materials, including more economically and environmentally sustainable concrete solutions.

The next step is to build a guiding coalition. A strong coalition of various stakeholders across the concrete value chain is necessary to communicate goals, barriers, and potential solutions and to drive change. Such a coalition can be established through:

- Involving various stakeholders in the team
- Leveraging trade associations
- Engaging early adopters (refer to this group defined previously in the DOI theory)

The third step is to develop a change vision. As stated previously, many industry associations have developed roadmaps with measurable outcomes and long-term goals.

The fourth step is to communicate the vision. The vision has already been communicated via various platforms, such as:

- Industry associations newsletters, conferences, meetings
- Industry conferences
- Technical and professional organizations such as ACI, AASHTO, ASTM, NRMCA

The fifth step is to remove obstacles. This could include:

- Risk assessment, with several key areas being:
  - Engineering risk, which can have obstacles removed by producing comprehensive engineering performance data
  - Environmental risk, which can have obstacles removed by producing verifiable environmental impact data
  - Cost risk, which can have obstacles removed by producing cost data
  - Scalability risk, which can have obstacles removed by assessing scalability to address agency demand data
  - Constructability risk, which can have obstacles removed by producing a demonstration of constructability
- Developing standard practice documents and tools
- Providing training and education
- Facilitating supply chain development and scale material production and certification

- Accelerating permitting and providing guidelines and training on how to obtain permits and meet regulatory standards.

The sixth step is to generate short-term wins. This step can include:

- Demonstration projects
- Recognize early adopters: awards and public recognition
- Communicate performance data broadly.

The seventh step is to maintain acceleration after initial wins. Examples of means to maintain acceleration are listed below. Continuing these efforts is crucial, as there are numerous examples of pilot projects that failed to become standard practice due to a lack of consistent implementation efforts.

- **Scaling-up initiatives**: Transition from demonstration projects to pilot projects implemented on city, county, or state networks.
- **Post-construction debriefs**: Make debriefing with all involved parties a standard practice. For example, after each project, workshop, or activity, conduct a debrief to evaluate what was done well, identify areas for improvement, and determine actions to avoid in the future.
- **Ongoing training and support**: Ensure continuous training and share performance data to keep all stakeholders informed and engaged.
- **Feedback loops**: Learn from early adopters to refine the technology and products, aiming to minimize the effort required on the adopters' end while enhancing overall effectiveness.

Finally, institutional change is achieved when the change is embedded into industry practice and a lasting adoption is ensured, which can include:

- Integration into building codes and DOT specifications
- Monitor performance and continuously improve specifications.
- Align federal, state, and local efforts in creating task force groups and regional training centers to support DOTs in updating lab equipment test methods, revise and update specifications, and design tools.

3. Review of Technology Development Tracking Systems and Funding Mechanisms

3.1 Chapter Overview

This chapter examines three key models for assessing the maturity and investment readiness of emerging technologies, with a focus on their application to new types of concrete, which are more durable, cost effective and better for the people and the environment. The Technology Readiness Level (TRL) system, developed by NASA, evaluates technologies from concept (TRL 1) to commercialization (TRL 9). The Investor Readiness Level (IRL) model complements the TRL by focusing on the financial milestones necessary for securing investment, helping investors align funding with a technology's development phase. Finally, the Valley of Death (VoD) model highlights the funding gap between early development and market commercialization. Bridging this gap requires support from government grants, partnerships, and industry collaboration. Together, these models provide a structured approach to navigating both technical and financial challenges in advancing new technologies to market and provide insights into framework development for these materials.

3.2 Technology Readiness Level (TRL) System

TRL is a systematic framework developed by the National Aeronautics and Space Administration (NASA) in the 1970s to assess the maturity of a particular technology, from concept to fully deployed system. Each TRL is associated with a different stage of development, which can help inform funding decisions at each level. The nine levels are:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
- TRL 4 – Technology validated in the laboratory
- TRL 5 – Technology validated in relevant environment (industry relevant environment)
- TRL 6 – Technology demonstration in a relevant environment
- TRL 7 – System prototype demonstration in an operational environment
- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven to be successful in an operational environment

They are often grouped into three areas of technology research, including feasibility and proof of concept studies (TRL 1-3), technology development, including prototyping and demonstration from lab scale at TRL 4 to scaled up demonstration at TRL 6), and finally, final system development, verification and qualification leading to commercialization (TRL 7-9). These groups are illustrated in Figure 5.

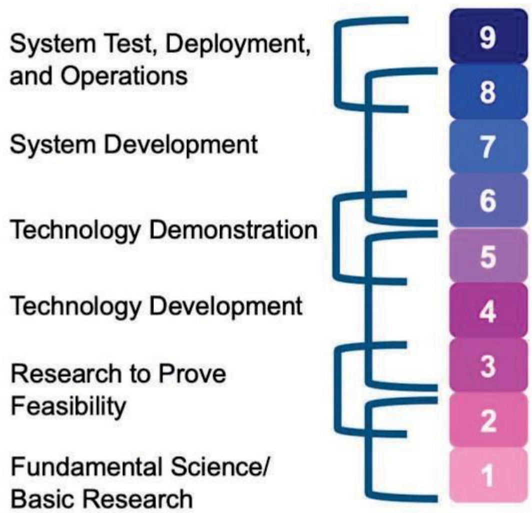

Figure 5. Illustration of TRL regenerated from reference (*17*).

In terms of stages of funding, early TRLs (1-2 or 1-3) typically receive funding from research grants, government programs, and academic institutions. Mid-stage TRLs (4-6) often attract venture capital or private funding for prototype development, while late-stage TRLs (7-9) may seek funding from industry partnerships or commercialization efforts.

The TRL classification system has been criticized for several reasons. Its scope is narrow and focuses mainly on technical development. For example, it does not address barriers to adoption, nor does it account for market readiness, cost-effectiveness, durability, and long-term performance. There is also a lack of any consideration for environmental and social impacts, resource availability, progress toward conformance with specifications, cost-competitiveness, and supply chain development. However, TRL has the advantage of having become widely adopted and widely known in any field of application.

3.3 Investor Readiness Level (IRL) System

The Investor Readiness Level model mirrors the TRL system but focuses on the technology's readiness to attract different types of investors (see Table 1). It helps investors understand the stage of development and potential risk, aligning their funding with the technology’s progress *(Burkett, 2017)*. The IRL ranking system is less commonly known and used than the TRL ranking system.

Table 1. Investor readiness levels.

Level	Definition
IRL 1	Basic principles of interaction are observed and reported.
IRL 2	Application and interaction concept formulated.
IRL 3	Analytical and experimental proof of interaction concept.
IRL 4	Component integration and validation in the laboratory environment.
IRL 5	System/subsystem/component validation in a relevant environment.
IRL 6	The prototype demonstrated in a relevant environment.
IRL 7	System prototype demonstrated in an operational environment.
IRL 8	The actual system completed and qualified through test and demonstration.
IRL 9	Actual system proven through successful mission operations.

3.4 Valley of Death Concept

The Valley of Death (VoD), a model presented in Gbadegeshin et al. (2022) *(Gbadegeshin et al., 2022)*, refers to the critical gap between initial funding (e.g., research grants, seed funding) and later-stage commercial funding (e.g., venture capital, industry partnerships) when a new technology is ready for commercialization but still unproven in the market (see schematic in Figure 6). Early-stage technologies often struggle to secure funding in the VoD because they require significant capital to scale, but the risk is still high, and the market potential is unproven.

Government grants, bridge loans, and strategic partnerships are essential to help companies cross this gap. Sources of funding to support industries in this period are public-private partnerships, government commercialization grants (e.g., Small Business Innovation Research [SBIR] programs discussed later in this report), or collaboration with industry players.

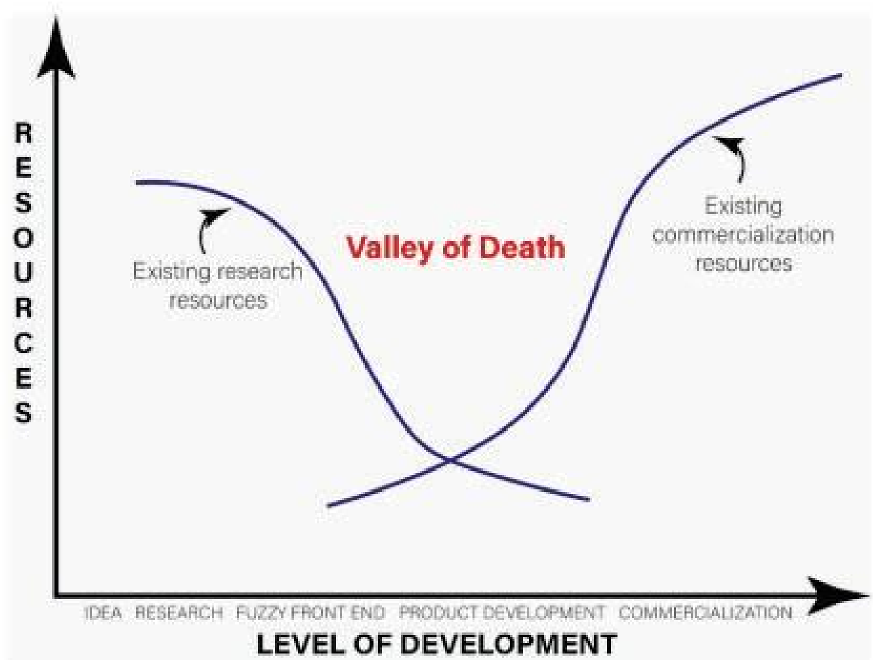

Figure 6. Illustration of Valley of Death concept from reference (*19*).

4. Review of Some Implementation Programs

4.1 Chapter Overview

This chapter provides an overview of inter-agency initiatives focused on past successful programs and initiatives focused on the accelerated implementation of new materials or technologies. The reviewed programs include:

- The Superpave
- Performance-engineered concrete mixes
- AASHTOWare PavementME software

In addition to these targeted pavement efforts, broader accelerated programs in manufacturing and energy are also discussed. These programs highlight innovative approaches to material development and infrastructure improvements. A section on lessons learned is provided at the end to synthesize the insights gained from these initiatives and their relevance to future implementations such as new concrete materials.

4.2 Implementation of Superpave in the U.S.

The implementation of Superpave for performance grading of asphalt binder across the U.S. by AASHTO was a coordinated, phased effort aimed at ensuring states and local agencies adopted the new technology for better-performing asphalt pavements. AASHTO played a central role in guiding this implementation through leadership, training, technical support, and collaboration with state departments of transportation (DOTs) and industry partners. Below are key phases on how AASHTO implemented the Superpave system across the U.S.:

1. Technical Guidance and Standards Development

AASHTO was responsible for developing and publishing the technical specifications and standards for Superpave. This included the AASHTO M 320 standard *(American Association of State Highway and Transportation Officials (AASHTO), 2021a)*, which defines the Performance Graded (PG) binder system and AASHTO R 35 *(American Association of State Highway and Transportation Officials (AASHTO), 2021b)*, which provides guidelines for mix design.

These standards ensured consistency in the use of Superpave technology across states and encouraged the adoption of uniform practices for asphalt mix design, material selection, and testing.

2. Collaboration with State DOTs

AASHTO worked closely with state DOTs to encourage and facilitate the adoption of Superpave. State DOTs were key stakeholders in the system's successful implementation, as they were responsible for specifying asphalt materials and construction methods.

AASHTO provided technical resources and training to state DOTs to help them transition from traditional asphalt mix designs to the more advanced Superpave system.

3. Superpave Regional Centers

To support implementation on a regional level, AASHTO helped establish five Superpave Regional Centers across the U.S. These centers provided hands-on training, research, and technical support to state agencies and contractors.

The centers also helped with performance evaluations and field trials, allowing state DOTs to understand better how Superpave mixes would perform under their specific climate and traffic conditions.

4. Superpave Implementation Team (SIT)

AASHTO formed the Superpave Implementation Team (SIT), a national task force composed of representatives from federal agencies, state DOTs, academia, and industry. The SIT coordinated efforts to roll out Superpave nationwide, addressing technical challenges and providing policy recommendations. The SIT was responsible for monitoring the progress of Superpave implementation, identifying barriers to adoption, and ensuring that state agencies had the resources they needed to adopt the new system.

5. Training and Certification Programs

AASHTO, in partnership with the Federal Highway Administration (FHWA), conducted extensive training programs for state DOT engineers, contractors, and technicians. These programs included workshops on the Superpave mix design process, binder selection, and performance testing.

Certification programs were established to ensure that personnel responsible for testing and producing Superpave mixes had the necessary skills and knowledge to implement the system correctly.

6. Pilot Projects and Field Testing

Pilot projects were critical to the implementation of Superpave. AASHTO worked with state DOTs to conduct field trials in various regions of the U.S. These trials tested Superpave mixes under real-world conditions and provided valuable data on the performance of the system in different climates and traffic conditions.

Other states shared lessons learned from these pilot projects, which helped refine the Superpave system and build confidence in its effectiveness.

7. Federal Support and Funding

AASHTO collaborated with the FHWA to secure federal funding for the widespread adoption of Superpave. The FHWA allocated funds through the Intermodal Surface Transportation Efficiency Act (ISTEA) and other transportation bills to support the development of Superpave technology and its deployment at the state level.

This financial support helped state DOTs invest in the necessary equipment and training to transition to the Superpave system.

8. Equipment Standardization

AASHTO led efforts to ensure that laboratories and contractors had access to the appropriate testing equipment for Superpave. These efforts included specialized equipment for measuring binder performance and aggregate properties, such as the Superpave gyratory compactor (SGC), which is essential for creating Superpave asphalt mixes.

By standardizing equipment and ensuring its widespread availability, AASHTO helped state agencies and contractors align their practices with the new requirements.

9. Continued Research and Improvement

Even after Superpave was initially implemented, AASHTO continued to support research and development efforts to refine the system and address any issues that arose during implementation. The National Cooperative Highway Research Program (NCHRP) *(Transportation Research Board, 2024)* and other AASHTO-led research programs provided ongoing support to improve Superpave's performance and adapt it to new challenges. AASHTO also updated the Superpave standards regularly based on new findings and feedback from the field.

4.3 Performance-Engineered Concrete Mixes (PEC)

PEC was implemented as part of an effort to improve the quality, durability, and sustainability of concrete used in infrastructure projects, particularly for pavements. The FHWA, in collaboration with state DOTs and research institutions, championed the initiative. Key steps in implementation included:

- Shift from Prescriptive to Performance-Based Specifications: Traditional concrete mix designs were based on prescriptive standards, which specified ingredient proportions without focusing on the actual performance of the concrete in service. PEC shifted the focus to performance-based specifications, where concrete is designed to meet specific performance criteria, such as strength, durability, and shrinkage, depending on the project's needs.

- Collaboration with Research and Industry: The PEC initiative was implemented through partnerships between research bodies (such as the National Concrete Pavement Technology Center), government agencies, and private industry. These stakeholders worked together to define performance indicators that could guide the concrete mix design process to ensure it met the necessary criteria for durability and workability.
- Use of New Test Methods: To support performance-based concrete, new testing methods were introduced to assess properties like cracking resistance, strength development, and durability under various environmental conditions. These tests were conducted both in the laboratory and on pilot projects to validate the concrete's real-world performance.
- State-Led Projects: Several state DOTs played a pivotal role in implementing PEC in real-world infrastructure projects. For instance, states like Iowa, Minnesota, and Wisconsin incorporated PEC mixes in concrete pavement projects to ensure better long-term performance and reduced maintenance needs.
- Education and Training: The transition to PEC required training for engineers, contractors, and transportation officials to understand performance-based mix designs and how to implement them. Workshops and training sessions and the National Concrete Consortium (NC^2) were held to educate professionals and maintain feedback loops to collect information about the benefits, challenges, test procedures, and specifications related to using PEC.
- Data Collection and Feedback: As PEC was implemented, data from pilot projects and full-scale applications were collected to fine-tune the approach. Feedback from these projects helped refine performance metrics and testing procedures, ensuring that the concrete mix designs met both short- and long-term performance goals.

4.4 AASHTOWare Pavement ME Implementation

AASHTOWare Pavement ME ("AASHTOWare Pavement ME Design," 2023) is a pavement design software developed by AASHTO to provide advanced and reliable tools for designing pavements. This software integrates mechanistic-empirical design principles, meaning it combines empirical data (from field and lab studies) with mechanistic modeling (which predicts pavement behavior under traffic loads and environmental conditions). Key Aspects of AASHTOWare Pavement ME Implementation are:

- Mechanistic-Empirical Approach: The Mechanistic-Empirical (M-E) approach used in Pavement ME provides more accurate predictions of pavement performance by considering site-specific factors, such as traffic loads, climate conditions, and material properties. This allows engineers to design pavements with a more reliable prediction of how they will perform over time under actual service conditions.

- Data-Driven Performance: Pavement ME uses extensive data from long-term pavement performance (LTPP) studies, incorporating data from thousands of test sections across the U.S. This empirical data is used to validate mechanistic models and enhance the accuracy of pavement life predictions. The pavement performance data from the California state highway network and various test tracks has been used to calibrate the PavementME design tool for concrete pavement design and the CalME tool for asphalt pavement design for California Department of Transportation (Caltrans) *(Ullidtz et al., 2006; Wu et al., 2018)*.
- Design Flexibility: The software allows for the design of different types of pavements, including flexible pavements, rigid pavements, and overlays. This versatility supports the design of new pavements as well as the rehabilitation of existing ones.
- Performance Prediction: One of the critical features of Pavement ME is its ability to predict pavement performance over time, including factors like rutting, cracking, and roughness. These predictions help state DOTs and engineers make informed decisions regarding the thickness and material composition of pavements to ensure long-term durability.
- Implementation by State DOTs: AASHTOWare Pavement ME has been adopted by some state DOTs across the U.S. for designing highways and roadways. States like Florida, Virginia, and Minnesota have led the way in using the software for optimizing pavement designs tailored to their specific climates, traffic patterns, and materials.
- Training and Support: To support the adoption of Pavement ME, AASHTO and partnering organizations provide training sessions, user manuals, and technical support. Engineers and state agencies are trained on how to input local data, interpret results, and use the software to create efficient, cost-effective pavement designs.

4.5 Materials Genome Initiative (MGI)

There are several inter-agency efforts beyond those tied to pavements. The Materials Genome Initiative (MGI) ("Materials Genome Initiative | WWW.MGI.GOV," n.d.) is a U.S. federal multi-stakeholder initiative launched in 2011 to accelerate the development and deployment of new materials twice as fast and at a fraction of the cost compared to traditional methods. MGI targeted several key areas of materials innovation, including:

- Lightweight metals and alloys for transportation and aerospace industries.
- Advanced composites for energy-efficient vehicles.
- High-performance materials for energy storage and generation (e.g., batteries, solar cells).
- Biomaterials for medical applications, such as tissue engineering and drug delivery systems.

The primary focus has been advanced metals, polymers, and composites. Key objectives of the MGI include:

- Accelerating Discovery: The MGI sought to reduce the time required to discover, develop, and deploy new materials from decades to a matter of years. This was done by integrating computational modeling, data management, and experimental tools to streamline the research process.
- Collaboration Across Sectors: The initiative promoted collaboration between government, industry, and academia to share data and research in a way that would benefit all sectors. By pooling resources and knowledge, the goal was to break down traditional barriers to innovation in materials science.
- Open Access to Data: A key aspect of MGI was to encourage the creation and use of open-access databases, where researchers could share experimental and computational data on material properties. This open-access approach allowed the scientific community to leverage past research to speed up the discovery process for new materials.
- Multiscale Modeling and Simulation: One of the central goals of the initiative was to develop and apply multiscale modeling techniques, allowing scientists to predict the properties of materials at different scales—from atomic structures to macroscopic systems. This approach greatly reduced the reliance on trial-and-error experiments.

Several organizations support MGI in various ways. These organizations include:

- Department of Energy (DOE)
- Department of Defense (DOD)
- National Science Foundation (NSF)
- National Institute of Standards and Technology (NIST)
- National Institute of Health (NIH)
- National Aeronautics and Space Administration (NASA)

Programs under MGI emphasized speeding up the traditional materials development cycle through a combination of:

- High-throughput experimentation,
- Advanced computational techniques,
- Data-sharing platforms to allow researchers to build on each other's work more effectively.

By focusing on open innovation and collaborative research, MGI aimed to reduce the time and cost of bringing new materials to market, which could have major implications across various industries. It fostered the integration of experimental and computational tools to create a "materials innovation ecosystem" that could respond more quickly to the evolving needs of sectors like clean energy, advanced manufacturing, and national security.

4.6 Summary of Lessons Learned

4.6.1 Superpave Implementation

Standardized Guidelines and Technical Support: Superpave's success was driven by standardized specifications (AASHTO M 320 and R 35) and consistent technical support. For new types of concrete, it is crucial to develop and disseminate uniform standards to ensure consistency across regions.

Collaboration with State DOTs: AASHTO's close collaboration with state DOTs ensured effective adoption. Similarly, collaboration with DOTs for new types of materials will be critical in encouraging widespread adoption.

Regional Support Centers: Establishing regional centers that provide technical training, testing, and research support could help accelerate the adoption of new types of concrete.

Pilot Projects: Pilot testing in various regions allowed Superpave to gain credibility through real-world performance data. Implementation of new concrete materials and technologies should follow a similar path, with pilot projects to gather data and refine practices.

4.6.2 Performance-Engineered Mixes (PEM)

Shift to Performance-Based Specifications: PEM moved from prescriptive to performance-based specifications, which aligns well with the approach needed for new types of concrete. Focusing on measurable performance indicators (e.g., durability, shrinkage, and strength) will ensure that new materials meet the necessary standards.

Collaboration and Advanced Testing: Like PEM, the implementation of new materials should rely on collaboration between research bodies, industry, and government, and advanced testing methods should be utilized to validate performance.

Training and Feedback Loops: Continuous training and real-world feedback loops are critical for refining new materials and ensuring they perform in diverse conditions.

4.6.3 AASHTOWare Pavement ME

Training and Support: Extensive training and support helped DOTs adopt Pavement ME effectively. Providing similar resources will be important for transitioning to new types of concrete.

4.6.4 Materials Genome Initiative (MGI)

Collaboration Across Sectors: MGI emphasized collaboration between academia, industry, and government, which helped accelerate materials discovery. A similar approach will help bring new materials to market faster.

Open Access to Data and Multiscale Modeling: The success of MGI was bolstered by open-access databases and advanced modeling techniques. Establishing open platforms for sharing research and performance data on new materials will enhance innovation and reduce development time.

4.7 Review of Funding Programs

Various funding programs can be leveraged to fund the progression of materials suppliers from low TRLs to higher TRLs. Some of these funding sources for the suppliers are listed and discussed below.

4.7.1 SBIR and STTR

The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs *(US Small Business Administration, n.d.)* in the U.S. provides funding for early-stage technology development, particularly in the high-risk valley of death phase. These programs are designed to bridge the gap between early research and marketable products. The phases of funding include:

- Phase I: Early proof of concept, typically funded through government research grants.
- Phase II: Further development and prototyping with larger grants to prepare for commercialization.
- Phase III: No direct funding but seeks commercialization through private sector or government contracts.

4.7.2 Advanced Research Projects Agency-Energy (ARPA-E)

ARPA-E was created in 2009 by the U.S. Department of Energy to fund high-risk, high-reward energy technology projects. A key focus of ARPA-E is to accelerate the development of new materials for energy storage, grid resilience, and other energy goals with the following aims:

- Support early-stage research into advanced energy materials that could disrupt current energy systems.
- Accelerate the commercialization of new materials for lower impact energy.
- Foster collaboration between research institutions and private industry to scale new technologies.

ARPA-E funds projects related to advanced materials for energy storage, including new battery chemistries and supercapacitors, as well as materials for solar cells, fuel cells, and thermal storage systems.

4.7.4 Accelerated Implementation and Deployment of Pavement Technologies (AID-PT)

The AID-PT program is part of the Everyday Counts (EDC) initiative launched by the Federal Highway Administration (FHWA) during Obama's administration *(Federal Highway Administration (FHWA), 2024)*. EDC was designed to identify and promote underutilized innovations that could shorten project delivery time, enhance roadway safety, and reduce construction costs. Examples of focus areas include:

- Warm-mix asphalt
- Recycled materials in pavement, promoting the use of materials like recycled asphalt or concrete
- Intelligent compaction technologies
- By providing federal funding or grants, the AID-PT program helped states and municipalities overcome barriers to adopting new technologies more quickly. This grant program can help fund the later IRL (7-9).

Eligible entities for funding by this program include:

- State Departments of Transportation (DOTs)
- Metropolitan Planning Organizations (MPOs)
- Local Governments
- Federal Land Management Agencies (FLMAs)
- Tribal Governments
- Other public entities responsible for transportation infrastructure

This program can be applicable to the Pilot2Practice stage in the framework, as will be discussed in Chapter 6, and help innovators overcome the VoD area.

5. Risk Management and Getting to Standard Practice

5.1 Chapter Overview

This report addresses how to get innovative concrete into standard practice faster when dealing with the transportation infrastructure design and construction industry, which is often viewed as resistant to change and set in its traditional ways of doing things. Often, the perceived answer is to “get engineers and decision-makers to be less risk averse.” This answer does not address the fact that decision-makers and engineers are hired (and engineers are licensed) to avoid risk to an acceptable level. Risk is uncertainty and can concern individuals and managers who specify and include new materials in designs because of fear of losing licensure, career advancement, employment, or increased daily work challenges. For agencies, companies, and contractors, risks could be financial liability, litigation, loss of revenue, and damage to reputation. For getting innovative concrete into standard practice, there is primarily uncertainty regarding safety, engineering performance, scalability, constructability, cost, and environmental performance. At a high level, the following can be done based on decades of innovation, development, communication, and implementation efforts at international, national, state, and local levels:

> *Risks must be identified, addressed, and then managed at a much faster pace through a comprehensive yet cost- and human resource-efficient program.*

A general principle of risk assignment in planning and engineering practice is that the practitioner is not legally liable for problems that occur from their decisions if they follow an “accepted standard of practice,” and the practitioner, and potentially the organization that employs them, but not always, is responsible for decisions made that are outside accepted standard of practice. To emphasize, this responsibility falls to the individual who makes each decision outside of standard practice, or in some cases, the consequences of negative risks are formally accepted at some other higher level within an organization. This chapter discusses the steps that must be taken to assess and mitigate risks to accelerate the adoption of new technologies.

5.2 Getting to Standard Practice

In engineering practice, incorporation of innovation into standard practice and legal protection for the engineer means inclusion in all the practice documents and tools that a practitioner uses to perform their work, such that a practitioner does not have to identify something as an innovation when included in a project, it’s just standard practice! As risks of innovations are evaluated at a faster pace, decisions must be made regarding which innovations to move forward to the next steps, and resources used to move innovations forward need to be applied at a faster pace. The innovation implementation theory (DOI) presented in earlier chapters of this report addresses the push and pull of motivation and handling of risk at the market and organizational levels. In practice, many professionals must make the transition from "no" to "maybe but not yet" to "yes" for the inclusion of innovation in standard practice. These professionals play different roles and have different responsibilities, acting individually or in committees.

There are a series of documents and tools that make up the standard practice. As an example, for the California Department of Transportation (Caltrans), the list of documents and tools that must be updated for the inclusion of an innovative concrete material into standard practice will likely include:

- Material Safety Data Sheet (MSDS) meeting legal requirements for safety and Standard Operating Procedure (SOP) for handling and use of the material
- Materials specifications used by the practitioner's organization (not another organization's specifications), including:
  - Materials test methods (if updating is needed for the innovation)
  - Materials design tools (if updating is needed for the innovation)
  - Materials quality assurance (if updating is needed for the innovation), including:
    - Mix approval and limits for acceptance
    - Materials test limits for construction
- Engineering structural design tools approved for use by the organization, including:
  - Engineering properties, damage, and failure models applicable to the innovative material
  - Identification in the tool that the innovative material is approved for use
- Guidance document(s) relevant to the innovation issued by the organization or from others and approved for use by the organization. Examples for the California Department of Transportation include:
  - Pavement Guidance:
    - Highway Design Manual
    - Construction Manual
    - Maintenance Manual
  - Bridges and Structures
    - Construction Guidance:
      - Concrete Technology Manual
      - Control Shrinkage & Cracking Manual
      - Prestress Manual
      - Reinforced Concrete Construction Manual
    - Design Guidance
      - Bridge Design Memos

- Bridge Design Practice
- Memo to Designers

Some of these documents may not require updates, but they will likely need to be checked to determine if that is the case and signed off after that check is made. For innovations to be incorporated into each of these elements of the standard of practice, the risks that fall within each professional's or professional committee's role and responsibilities need to be adequately addressed. The changes need to be approved following the approval process to become part of standard practice in the list above that is under their care.

For public infrastructure, where there are no market competition motivations on the part of the owner's organization to innovate, innovation is particularly driven by top-down goal setting. This top-down goal setting can be influenced at the organizational level by the types of motivations discussed in previous chapters. It must be followed up by policy directives and then related performance metrics for groups and individuals within the organization. The committees and individuals responsible for bringing innovation into standard practice to meet goals, policies, and performance metrics must have an adequate understanding and assessment of risk before they will be willing to incorporate it into their part of standard practice if they have a choice. If they are told to incorporate the innovation without much risk assessment, then the person giving that order takes responsibility for the risk.

However, experience shows that success requires a documented standardized process that sufficiently addresses risk to move the approval process forward in a timely manner. Such a process includes milestones at which risk is signed off on, sub-processes for developing and updating standard practice documents and tools, a communication strategy, and schedule expectations built into it to keep the process moving. Without such a process, the same potential risks are often continually and repeatedly brought up, slowing innovation, and eventually killing it through inertia. Experience has also shown that critical steps are moving from early work to later stages of implementation that are missing from many implementation processes (see the Valley of Death model in Chapter 2). Another mode of inefficiency and failure to move innovations forward is when an innovation has not had sufficient early risk screening and is moved to larger scale implementation, such as expensive and human resource intensive field pilot projects, and problems leading to failure are found that could have been dealt with for much less money and effort at an early smaller scale stage. Too many of these failures result in greater risk aversion or just depletion of funding and human resources available for innovation implementation. This experience calls for a hierarchical approach, assessing risks initially on a small scale and then at increasingly large scales with more detailed risk assessment, which brings cost and time efficiency into the process so that more innovations can be screened. This hierarchical approach results in each innovation passing a level of risk assessment and will have greater certainty of success at the next level, commensurate with the increased cost and resource use at each level. Finally, the hierarchical approach will provide innovators with early feedback, which means lower risk for them of being forced to perform in an expensive field pilot before they have identified potential problems, and the risk that their innovation will be killed because they just were not ready.

The next chapter takes the knowledge gained from the behavioral models for technology adaption, the funding stage models for new technologies, and past implementation programs, combined with an understanding of risk management for engineering innovation, and incorporates it into the Lab2Slab2Standard Practice framework for increasing the pace of change in concrete innovation. Specific risks addressed in the framework are:

- Engineering performance (strength and durability)
- Environmental impact performance (outputs affecting regional weather, wastes, water, land use, air pollution, and other impacts)
- Scalability (availability of raw materials, supply chain, market competition, permits, regulations)
- Constructability (workability, setting time, strength gain rate)

In addition, the framework includes stepwise development of standard practice documents and tools so that when the process in the framework is successfully completed, the innovation becomes standard practice.

6. Lab2Slab2Practice: A Hierarchical Risk Assessment Framework

6.1 Chapter Overview

This chapter introduces a comprehensive framework for one-stop clearinghouse centers of excellence with satellite branches across the country dedicated to streamlining the adoption of innovative cement and concrete materials. Drawing on risk management principles and the relevant behavioral change models, the framework provides a stepwise approach for efficient assessment of innovative cement and concrete for accelerated implementation, ultimately advancing them to standard practice.

Each regional center will follow the same step-by-step framework to put technologies through rigorous hierarchical assessments, delivering training resources and performance data for stakeholders as the technology scales up in production. Viable technologies will be transitioned to DOTs and other implementers for integration with standard practices. The centers are envisioned to be funded through sustainable private-public partnerships, with state DOTs receiving federal support to pilot and integrate promising technologies into standard practice.

The proposed hierarchical framework aims to reduce the implementation timeline from the typical 10 years or more to 2 to 5 years. While the framework presented is focused on concrete innovation and public transportation infrastructure, it can be adapted to other civil infrastructure and other materials and technologies. The framework can be followed to establish similar centers internationally.

The framework is discussed in detail in this chapter.

6.2 Establishing Lab2Slab2Practice Center

6.2.1 Getting Started: Building Urgency and Alliance

Build a sense of urgency: according to Kotter's model, building a sense of urgency is essential to forming a guiding coalition that engages a broad range of stakeholders. Below are examples of factors that underscore the urgency of adopting innovative materials, with a focus on the need to be aware of policy and market changes specific to them nationally and in California and take timely actions accordingly.

- Material Supplies Availability and Supply Chain Resilience:
    - While fly ash and slag from other states and countries are currently cost-competitive, the price may increase in the future due to global inflation and supply shortages. Other factors, such as geopolitical tensions and logistical bottlenecks, could further disrupt fly ash and slag imports, underscoring the

need for diversifying supply chains and exploring alternative SCMs (e.g., natural pozzolans and calcined clays, ground glass, and other locally sourced materials) to ensure continued SCM availability.

- Complying with Procurement Policies:
  - Focus on the impact of green procurement policies on market competitiveness and potential regulations targeting the importation of slag for California's construction sector and in several other states with large markets for cement.
  - Communicate the urgent need to collect the data to produce EPDs and work on reducing the environmental impacts from concrete products at various plants to meet upcoming new concrete classification and remain competitive in those states with green procurement markets.
  - To remain competitive in the market, both in terms of importation of cement products and where applicable to comply with green procurement policies, producers may need to source local and regional materials to diversify operations and increase access to SCMs while also cutting down transportation costs and the environmental impacts from concrete.

Build a guiding coalition: for sustained and meaningful progress, a coalition of diverse stakeholders, including researchers and academics, materials producers, materials purchasers, non-governmental organizations, project owners from private, local government, state, and federal government agencies, as well as regulatory agencies is needed. This coalition will play a pivotal role in identifying barriers and opportunities, shaping the centers' strategic vision and annual plans, and supporting information dissemination. To derive value from this coalition, several key aspects are needed:

- Technical Advisory Board:
  - Comprised of early adopters, such as large tech and manufacturing companies with extensive concrete usage (particularly those who are currently importing SCMs), design firms, general contractors, engineers, life cycle assessment (LCA) consultants, and state, local, and federal government. The board should also include representatives from trade associations, experts (academia or industry), ready-mix concrete producers, and national SCM manufacturers. This diverse group will ensure a broad range of perspectives and expertise.
  - The advisory board will be structured with a mix of paying affiliate members and voluntary members, fostering both financial sustainability and committed participation from key stakeholders.
- Inter-Agency Collaboration and Public-Private Partnership for Funding and Implementation:
  - Coordinated efforts across federal, state, and industry stakeholders, the adoption of new concrete technologies will depend heavily on inter-agency

collaboration, including state DOTs, DOE, FHWA, General Services Administration (GSA), White House, NSF, United States Geological Survey (USGS), and other agencies.
  - Leverage relations with industry to develop public-private partnerships to ensure funding sustainability and increase buy-in from industry.

Develop a change vision: the center and its satellite branches must define actionable visions and annual strategic plans with measurable performance metrics to sustain meaningful and measurable progress toward technology implementation. These metrics could focus on targets such as specific performance improvements, cost reductions, supply chain risk improvements, and where applicable, percentages of environmental impact reduction or the number of sustainable materials adopted. To ensure application and forward momentum, the development timeline, milestones, and deliverables will be key to success. Additionally, having built-in feedback loops to understand, assess, and reevaluate will be essential.

The feedback loop can be achieved through continuous communication with the advisory board, as discussed above. This includes:

- Continuously gathering feedback from advisory and other stakeholders, and updating the vision (i.e., framework and roadmap)

6.2.2 Document Then Clearly Communicate

6.2.2.1 Dissemination of Assessment Results at Each Step

Documentation of results: New materials and technologies are often introduced through small demonstration testbeds, but without a centralized, credible center for assessment, documentation, and dissemination, these testbeds often go unnoticed by key stakeholders, hindering implementation and adoption. Therefore, documenting assessment results, broadly disseminating the findings at each stage, and evaluating the effectiveness of information dissemination will be crucial for successful technology adoption.

To address this shortcoming, the centers need to publish and produce quality technical reports and journal papers while communicating the outcomes through various platforms that reach a broad range of stakeholders. Performance data should be documented and communicated broadly at each stage of development (Lab, Slab, Pilot) through specific actions such as:

- Communicating results directly to the supplier (innovator) to address any issues identified, optimize or customize the technology for the application, and prepare for the next stage.
- Writing annual (or semi-annual) technical reports that summarize the results of testing and evaluation, including assessments and any additional work needed to advance to the next step.

- Summarizing and highlighting key findings in concise technical briefs for broader accessibility.
- Preparing videos of laboratory testing, construction, and related activities, along with news blurbs, to engage a wider audience.

Platforms for Dissemination: To maximize the impact of dissemination efforts, the centers should leverage a range of platforms, including:

- Centers' Websites and Listserv: Use the centers' websites as a central hub for sharing reports, videos, webinars, and other resources. Utilize the listserv to regularly update stakeholders on new developments, events, and publications.
- Focused Area Conferences: Engage with targeted conferences to present findings and innovations.
- Professional Conferences: Present research and updates at major conferences, including:
    - American Concrete Institute (ACI),
    - California Construction and Industrial Materials Association (CALCIMA),
    - FHWA user group meetings,
    - Transportation Research Board (TRB) webinars and annual meetings,
    - Annual Nevada Infrastructure Concrete Conference,
    - National Concrete Consortium (NC^2),
    - American Concrete Pavement Association (ACPA),
    - NRMCA's ConcreteWorks,
    - IEEE-IAS/PCA Cement Conference,
    - Southwest Concrete Pavement Association (SWCPA) annual conference
    - ACI NEU Center of Excellence for Carbon Neutral Concrete.
- Architect and Engineer Outreach: Conduct presentations for architecture and engineering audiences, such as the American Institute of Architects, to raise awareness of new materials and practices.
- Policy and Funding Advocacy: Provide presentations to policymakers and funding agencies to secure support and resources for new material initiatives.
- Leverage NGO and Foundation Outreach: Offer webinars and presentations organized by non-governmental organizations (NGOs) and foundations to broaden the reach and impact of new technologies.
- Social Media: Leverage social media platforms to reach a wide audience and increase engagement with key stakeholders.

6.2.2.2 From Knowledge to Know-How: Developing Training Resources

In addition to presentations and publications to disseminate the findings and performance data, targeted training modules and short courses need to be produced and customized to address the needs of each stakeholder. Examples are discussed below.

Training for Ready-Mix and Dry-Cast Producers and Contractors

These training courses can be given in collaboration with existing support networks, for example:

- Engage with existing peer support networks and forums (for example, regional ACI chapters and NRMCA certification programs), or create new ones, if needed, where producers share experiences and find solutions to challenges encountered with new types of concrete or technicians who received training and are certified.
- Offer direct technical support from material suppliers or experts who can assist with practical issues and mix design, reducing the perceived effort required for troubleshooting.

The training courses should cover all aspects of implementing a new technology. Some of these aspects are discussed below as examples.

<u>User Safety, Hazardous Waste, and Special Handling</u>

- Employee Training: In addition to reviewing SDSs and evaluating environmental risks, ensure comprehensive training programs are in place for workers handling new materials. This training should include proper use of personal protective equipment (PPE) and safe handling procedures for both new admixtures and cement alternatives.
- Waste Disposal Protocols: Define clear protocols for the safe disposal of any waste generated during mixing or curing processes that involve new additives or alternative cements.
- Compliance with Environmental Regulations: Ensure that new materials comply with local, state, and federal environmental regulations, particularly related to hazardous waste disposal or emissions (e.g., volatile organic compounds from certain admixtures).

<u>Adjusting Standard Practice</u>

- Adjustments to mixing: Evaluate workability, ability to hold edge for slipform paving, and slump retention, especially in hot weather paving
- Adjustments to delivery and placement: Determine handling changes that may take place as a function of material or supply chain differences.
- Evaluate compatibility with chemical admixtures, if needed, run trials with other admixtures (different types of plasticizers and air entertainers)
- Evaluate setting time and any requirements for accelerator or set retarder

- Evaluate the strength gain rate and the possibility of admixtures to enhance strength if needed
- Evaluate the need for shrinkage-reducing admixtures
- Assess the level of mechanical properties loss and determine strategies to enhance strength (internal curing, fibers, more grinding to increase surface area, surface activation with targeted chemical groups)

Storage and Handling

- Moisture Sensitivity: Assess the moisture sensitivity of the materials. Some alternative cements or additives might require more climate-controlled storage conditions to prevent clumping or premature hydration, increasing costs.
- Additional Equipment Needs: Ensure that equipment (such as silos or new chemical dispensers) is compatible with the material properties or additional storage and other equipment is needed.
- Logistics Planning: Consider logistics and supply chain requirements. Identify any lead time adjustments or transportation challenges due to the sourcing of alternative materials that may not be as readily available as traditional components.

Training for Decision Makers and Implementers

Collaboration and Support Networks

- Create peer support networks or forums where engineers and architects can ask questions, share experiences, and find solutions to challenges encountered with new types of concrete.
- Offer direct technical support from material suppliers or industry experts who can assist during the design phase, reducing the perceived effort required for troubleshooting.

New Specifications

- Standardization of Performance Metrics: Establish clear performance metrics tailored to new types of concrete (both initial and impact on life cycle), such as: performance in terms of concrete short and long-term properties, cost, and environmental impact.
- Documentation and Certification: Implement standard documentation processes for material approvals and certifications and regional benchmarking to support decision-making.

Laboratory Verification Processes

- Cement and SCM Verification and Long-Term Monitoring Tools: Equip laboratories with tools, human resources, and equipment to measure reactivity and long-term performance metrics such as alkali-silica reactivity, drying shrinkage and crack propagation, freeze-thaw durability and chemical and salt deicer exposure durability.
- Cross-Department Collaboration: Promote collaboration between engineering, environmental, and procurement teams to ensure that laboratory processes align with cost, constructability, and sustainability goals and meet regulatory requirements for new materials.

Training for Engineers and Architects

Technical Guidance

- Technical guidelines and best practices for integrating the new materials into designs.
- Easy-to-follow design manuals and tools for material selection, mixing, and application.
- Develop Specialized Software Tools
- Provide software plug-ins for commonly used design tools (e.g., AutoCAD, Revit, or BIM platforms) that support new concrete designs.
- Durability models for PavementME
- Materials libraries for PavementME
- LCA tool that simplifies the environmental impact assessment of using new materials and links the life cycle durability to environmental benefits.
- Conduct workshops, seminars, and online courses tailored specifically for engineers and architects. Focus these sessions on practical use cases, benefits, and the technical aspects of new types of concrete.
- Incorporate hands-on training with real-life scenarios where participants can learn through direct experience. This reduces perceived complexity and builds familiarity with the material.

Standards and Specifications

- Work with standards organizations (e.g., ASTM, ACI) to develop standardized test methods and codes that incorporate new types of concrete. When such standards are already in place, engineers and architects will feel more confident in specifying the material.
- Offer pre-approval or fast-track processes for designs that incorporate new materials, reducing the time and effort needed to gain regulatory approval.

6.2.3 Celebrating Success and Building Momentum

Develop post-win strategies: celebrating success aligns with Kotter's model toward adopting a culture of change across an organization. The application of this concept to the new cement and concrete centers could be the form of the following actions depending on the stage:

- Hold public open house events and tours to engage high-profile stakeholders, industry leaders, and policymakers, showcase early achievements, and gather support for the next stage,
- Work with trade associations to create appropriate awards to recognize early success through industry awards and recognition honoring the innovators and early adopters,
- Leverage media for public recognition and awareness and increase visibility and support by coverage in mainstream media, news outlets, local news channels,
- Engage stakeholders in construction or celebrate milestones such as construction, 1-year or 5-year anniversary,
- Work with policymakers to develop incentives for early adopters, such as tax credits, certificates, official recognitions, etc., to highlight success and engage a broader range of implementers.

6.3 Centers in Action: Hierarchical Assessment of Concrete Innovations

As outlined in Chapter 5, the hierarchical assessment of concrete innovations includes risk assessment and consideration of the four-prong approach to address risks. This framework includes a comprehensive risk assessment that addresses the following critical factors:

- Engineering performance
- Scalability to address market demand for concrete
- Constructability
- Environmental impact performance

A hierarchically structured approach is recommended to track the technology as it advances across the TRL continuum, as shown in Figure 7. The assessment begins at the Lab scale (TRL 3-4, bench-scale production) to the Slab scale (TRL 4-6, pilot production at about 1-2 tons), then to the Pilot scale, and ultimately to Standard Practice (TRL 7-9 full commercialization). Each step is discussed in detail in the sections that follow.

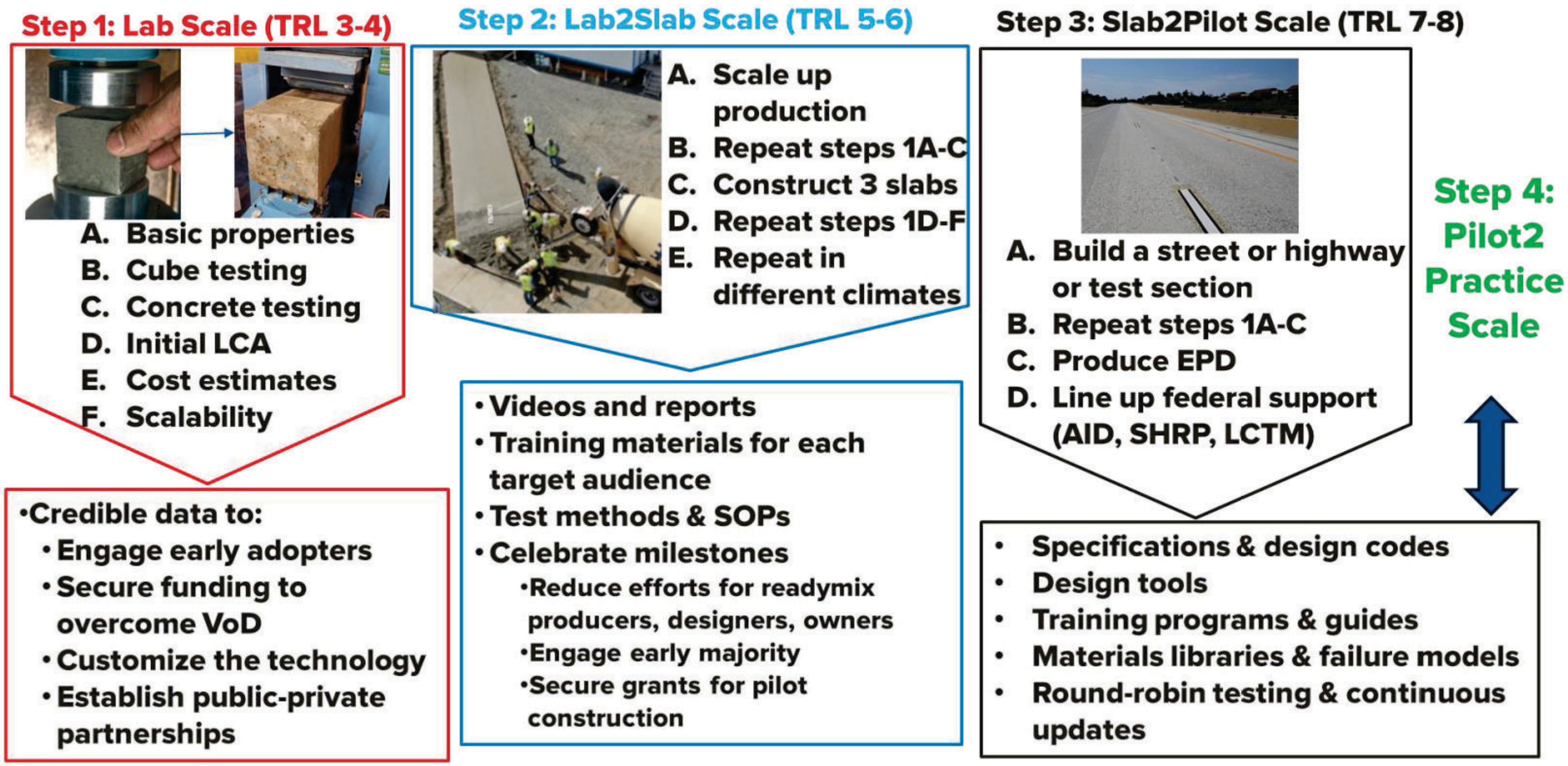

Figure 7. Overview of risk assessment framework: Lab2Slab2Practice to be followed by regional centers.

6.3.1 Step 1: Lab Scale (A Two-Stage Assessment)

6.3.1.1 Part 1 of 2 (Mortar/Paste: 1-2 lb of Test Material)

The material submitted for assessment is at the proof-of-concept stage (TRL 3), with production at the bench scale. Typical funding sources at this stage include personal investment, seed grants, and support from early adopters. The centers' assessment process at this stage includes the following steps:

- Engineering performance assessment:
  - Work with the suppliers to collect the materials and their associated safety data sheets. Sign any material transfer requirements.
  - Identify relevant standards (ASTM, ACI, AASHTO, etc.) or non-standard test procedures or develop new test procedures if needed. Characterize basic chemical and physical properties.
  - Perform testing and generate initial engineering performance data.
  - Modify physical or chemical properties (such as thermal, mechanical, chemical treatments, and others) if needed in close collaboration with the supplier.
  - Help the supplier customize the technology for specific applications (highways, streets, sidewalks, bridges, building foundations, etc.).
- Document, then Clearly Communicate: Perform the actions outlined in Section 6.2.1
- Make recommendations for the next step if the results warrant advancement.

The data provided by the center at this stage will support the innovator in identifying and securing additional funding sources to continue bench-scale production and research and development efforts to continue to customize and optimize the technology. Potential funding sources at this stage include programs state-level programs, and potentially federal programs such as SBIR/STTR, ARPA-e, DOE, etc. These funds will support the innovator to produce larger material quantities (buckets of materials) that can be tested in concrete in the next step.

6.3.1.2 Part 2 of 2 (Concrete: 1 Bucket of the Test Material)

The assessment to be done by the centers to move to TRL 4 (technology validated in the laboratory) should involve the following:

- Engineering performance assessment:
  - Collect materials and SDS from supplier, confirm physical and chemical properties again if a new source or batch,
  - Identify relevant standards for essential concrete testing (ASTM, ACI, AASHTO, etc.) and develop new performance-based test procedures if needed.

- Characterize concrete fresh and hardened properties:
  - Assess the workability, finishability, setting, and curing requirements of the concrete.
  - Evaluate hardened properties with age.
  - Perform accelerated durability testing to determine long-term performance in various environmental conditions.
- Perform multiscale modeling
- Predict engineering performance over the infrastructure's life cycle

- Initial cost estimates: the supplier performs an initial technoeconomic analysis for the bench scale production
- Scalability: perform an initial assessment of the availability of raw materials, other resources, permits, supply chain, and availability to support the concrete market (local, state-wide, regional, and beyond)
- Environmental performance: Collect the data to perform an initial environmental life cycle assessment for the bench-scale production. The supplier provides the data, and the centers can perform the LCA if not done by the supplier.
- Document, then Clearly Communicate: Perform the actions outlined in Section 6.2.1 appropriate for the stage
- Make recommendations for the next step if the results warrant advancement.

By the end of this step, viable technologies to advance to the slab scale are identified, and unviable technologies involving unfounded claims are filtered out. The data generated in this step are crucial to support the innovator in securing funding to scale up and overcome the valley of death.

6.3.2 Step 2: Slab Scale (No Structural Load) (1-2 tons of test material)

At this stage, it is expected that the supplier of a new material has advanced from bench-scale production to prototyping and is in the process of scaling up production (advancing from TRL 3-4 to TRL 5-6). The aim at this stage is to support the supplier in crossing the chasm identified in the DOI theory between early adopters and a larger group of adopters and secure funding for the plant crossing over the Valley of Death. The performance data from the centers is pivotal at this stage to ease the perceived efforts of the adopters, i.e., reduce fear of failure and perception of risks. The assessment done by the center involves the following steps:

- Engineering performance assessment based on a 3-slab construction:
  - Collect one or several tons (often delivered in super sacks) of material from the supplier with the SDS.
  - Confirm the physical and chemical properties of the received test material at this production scale.

- Identify candidate projects: centers' campus, local government, or developers. Applications can be any test pads such as sidewalks, driveways, or any other low-risk (no-traffic) flatwork.
    - Coordinate with local ready-mix concrete producers for production and delivery.
    - Coordinate with a local contractor to perform placement and finishing
    - Procure instrumentation and data acquisition system
    - Build slabs and assess constructability.
    - Instrument the slabs for environmental monitoring.
    - Assess compatibility with other concrete components, including admixtures, during mixing, transport, placement, finishing, and curing.
    - Assess hardened properties of concrete:
    - Evaluate production concrete performance: strength, durability, and other key properties depending on application.
    - Monitor the mid-term and long-term behavior of the material in the field in various climate conditions.
    - Round-robin testing and variability confirmation: repeat the same three-slab construction and testing frame in different climate areas (wet-freeze, dry-freeze, dry-no-freeze, wet-no-freeze) at satellite centers (could be done at the same time if feasible/appropriate) where the technology may be applicable.
- Cost and market competitive assessment: Identify the initial cost of material at this scale and expectations for cost reductions at the next scale.
- Scalability assessment: Assess the availability of raw materials, chemicals, fuels, and other resources required for production.
    - Identify bottlenecks in production and ways to remove them, such as grinding certification.
    - Determine if the technology displaces any existing recycling paths or processes and compare environmental impacts with those existing processes.
    - Support supply chain development and reliability: Evaluate proximity and access to material transportation modes, i.e., rail, and freight.
    - Determine progress toward obtaining permits and meeting regulatory compliance for scaling up production.
- Environmental performance assessment: Producer should be collecting the necessary data to generate an EPD at this stage.
    - The supplier can provide, in order of preference, a Type III A1 to A3 environmental product declaration (EPD), a third-party-verified life cycle assessment (LCA) (A1 to A3) with a clear assessment approach so parameters can be adjusted if they do not align with current product

category rules or sufficient proprietary information under a non-disclosure agreement for the center to perform an LCA. If the supplier cannot follow one of these pathways to environmental claim assessment, any environmental claims will be suspect.

- Document, then Clearly Communicate: perform the actions outlined in Section 6.2.1 appropriate for the stage
- Codes and standard:
    - Develop new non-standard special provisions and identify changes in design information, standard specifications, or standard special provisions and codes that would need to be made for slab scale implementation.
    - Produce draft versions of those documents necessary for Lab2Slab scale use for industry and agencies to review.
- Celebrating success and building momentum: repeat the steps as outlined in Section 6.2.1
- Prepare for the next step, if warranted by results

6.3.3 Step 3: Pilot Scale (With Structural Loads) (2-6 tons of Test Materials)

For the supplier to move to TRL 7 (system prototype demonstration in an operational environment) and TRL 8 (system complete and qualified), they must be operating at a pilot production scale, moving toward commercializing the material and beginning to profit from sales. The centers' work is outlined below:

- Engineering performance assessment: Identify a pilot project in coordination with local or state road agencies or regional centers with accelerated loading capabilities. These could include:
    - State DOTs' stationary heavy vehicle simulators, such as the one at UCPRC in Davis, CA
    - Test tracks such as MnROAD in Minnesota or NCAT track in Alabama and new test tracks similar to these in other states,
    - Mainline pilot test sections: sections embedded in construction projects on mainline highways or streets
    - Help local government or private owners apply for grants: AID, SHRP, LCTM, and state and federal programs available for implementation and sustainable practices.
    - Confirm the chemical/physical properties at scale production.
    - Repeat steps for engineering performance evaluation in the Slab scale.
    - Continue to collect data from demonstration projects
- Environmental performance assessment: centers collect an EPD for the material from the supplier. This should be a requirement at this stage.

- Document, then clearly communicate: repeat the steps as appropriate for this stage as outlined in Section 6.2.1
- From knowledge to know-how: developing training resources: repeat steps as appropriate for this stage as outlined in Section 6.2.1
- Celebrating success and building momentum: repeat the steps as outlined in Section 6.2.1
- Scalability and supply chain established
    - The supplier has performed a supply-demand analysis and is prepared to scale production to support identified markets.
    - The supplier has secured supplies of raw materials with economical transport modes (rail, barge, truck)
    - Distribution networks (cement plants or concrete producers) are established through partnerships with third-party logistics providers. Regional distributors or storage facilities may be needed.
- Cost analysis, market demand, and price benchmarking: the supplier performs technoeconomic analysis for plant production and establishes the cost of material at this scale and expectations for cost reductions at full scale.
    - The supplier works on assessing market competition, break-even study to establish profit margins, and sensitivity analysis to determine price and calculate the timeline of return on investments.
- Prepare for full-scale implementation if warranted by results

6.3.4 Step 4: Standard Practice Scale (Institutional Change)

At this stage, the centers' assessment work is completed and their focus shifts towards supporting implementing organizations to embed the technology into standard practices, driving institutional change, and ensuring it is widely accepted and utilized across the implementing organizations. The material is at TRL 9 (the actual system is proven to be successful in an operational environment). The centers will support implementing agencies in making these technologies part of routine operations by providing essential information and resources. The centers' work will focus on these actions:

- Support implementing agencies with the knowledge, data, and expertise needed to update their specifications, codes, and design practices, include them in technical guidance and consider them in the asset management system to go from Pilot2Practice.
- Documentation and Clear Communication: Effective documentation and communication are vital to ensure that stakeholders understand and accept the new practices following the steps outlined in Section 6.2.1.

- From knowledge to know-how: developing training resources: repeat steps as appropriate for this stage as outlined in Section 6.2.1. The centers will:
    - Develop Customized Training Documents: Create training materials tailored to different stakeholder groups: inspectors, contractors, and regulatory bodies, addressing their needs and concerns.
    - Collaboration with Regulatory and Standards Bodies: Work closely with regulatory bodies and standards organizations (e.g., American Concrete Institute) to ensure provisions for the materials are included in relevant codes and standards. This process may involve submitting data, research findings, and case studies to validate the technology and demonstrate its performance in real-world applications.
    - Incorporation into Specifications: Support the integration of the technology into material and construction specifications, ensuring that it becomes a recognized and standardized option for various applications.
    - Integration into Design Manuals, Catalogs, and Tables: Facilitate the inclusion of the technology in design resources such as manuals, catalogs, and tables, making it accessible and convenient for practitioners to use in routine design and planning.
    - Training and Professional Development: Offer targeted training through short courses, workshops, and seminars to enhance stakeholders' understanding and capability in implementing the new technology. These sessions may cover best practices, troubleshooting, and compliance with updated codes and specifications.
    - Laboratory Equipment Upgrades: Assess and, if necessary, upgrade laboratory equipment to accommodate verification testing of the new technology, ensuring that testing facilities are equipped to support reliable quality control and compliance.

7. Final Remarks: Essential Resources and Strategic Partnerships

7.1 Chapter Overview

The framework presented in this report aims to facilitate and accelerate the bridging of the gap between research and commercialization, often referred to in various models as the chasm or Valley of Death, to transition to new materials and technologies for cement and concrete into standard practice at a faster pace.

This chapter emphasizes the importance of providing resources to enable high-throughput and comprehensive testing and assessment. This chapter also underscores that establishing the proposed network of centers of excellence will require dedicated funding to either build new facilities or expand existing ones across the U.S., accounting for the country's diverse climates, regional construction material requirements, and transportation networks to move materials from source to manufacture to use site.

The importance of sustained support from both private and public entities to achieve the vision outlined in this report is discussed in this chapter.

7.2 Essential Resources and Funding Mechanisms

For the success of this framework, sustained funding is essential to ensure that the centers have the resources needed to support high-throughput experimentation and consistent output generation each year, as was found successful in the Materials Genome Initiative. Operating centers with intensive testing and assessment capability and then moving to larger-scale construction efforts require substantial human resources, as well as well-maintained equipment and facilities.

To achieve fast throughput, these centers must go beyond small laboratory capabilities and be equipped with industrial-scale equipment, including large ovens and kilns, milling, crushing, and grinding equipment, industrial sieves and screening machines, benchtop and drum mixers, hydraulic test frames, room with proper ventilation, air-conditioned, with dust control, and environmental rooms with controlled temperature and humidity cycling over a large range, freeze-thaw cycling rooms, carbonation chambers, space and facilities to handle large concrete and water waste management continuously. Additionally, continuous supplies of aggregates, cement, and admixtures, as well as storage spaces, are necessary.

Furthermore, centers must either own or have access to advanced analytical capabilities, such as X-ray fluorescence (XRF), X-ray diffraction (XRD), particle size analyzers, microscopic imaging equipment, isothermal calorimeters, thermogravimetric analyzers, and many others. Establishing and maintaining centers with these capabilities requires a significant amount of equipment, human resources, and infrastructure, as well as a large outdoor and indoor space, requiring significant investment.

While some similar initiatives exist in the U.S. through congressional earmarks, no center currently operates at this envisioned scale. Realizing this model would require a collaborative funding approach across governmental and private sectors. Possible funding sources include intra-agency partnerships between the FHWA and DOE, pooled funds from state DOTs, and support from private-sector project owners. Some existing centers that are available with similar capabilities at a smaller scale can be retrofitted and upgraded to increase capacity and throughput rate.

Additional investment may come from private project owners, such as data centers, manufacturers with large industrial facilities, and commercial real estate developers, uniquely positioned to drive demand for sustainable concrete solutions, as their projects often have high concrete requirements. Their investment in the centers is crucial to ensuring commitment and buy-in, as well as eventual implementation on a broad scale. Investment from these parties will be essential in overcoming the Valley of Death (the funding gap between research and commercialization) for new cement and concrete materials.

Similarly, investment and expertise from the concrete and construction industry (large contractors, design firms, ready mix, and drycast producers) are key to increasing their commitment and buy-in, which is key to implementation and adoption. Collaboration with industry was a cornerstone of Superpave's success, with industry stakeholders playing an active role in performance testing, equipment standardization, and research. Industry expertise is essential in creating effective feedback loops and providing validation of test methods and materials in large projects in the field, developing or modifying existing standards and test procedures, and refining materials and technologies.

7.3 Federal and State Alignment for Pilot and Standard Practice

To achieve wide-scale adoption of new materials as a standard practice among DOTs across the country, there must be alignment between federal/national and state agencies and organizations, or at least between state agencies. Superpave implementation benefited from close collaboration between AASHTO and state DOTs. One of the key elements of Superpave's success was the creation of Superpave Regional Centers to provide hands-on training, technical support, and performance evaluations. The proposed Lab2Slab2Standard Practice centers in this report are designed to serve a similar purpose, providing critical support for the implementation of new concrete technologies. Alternatively, companion federally and state-funded regional centers could further assist by transitioning the materials at later stages and overseeing and facilitating the transition from Slab to Pilot and then to the Standard Practice scale.

For states to successfully pilot new materials within their networks, federal support will help in moving forward quickly. State DOTs need funding to cover the costs associated with pilot projects, including additional quality control measures, monitoring, data collection, and analysis. Additionally, grants and financial resources should be made available for local governments to pilot these innovative materials in their infrastructure projects. State and local governments will require resources for essential upgrades, such as laboratory verification equipment, quality control protocols, and updated testing methods. In the potential absence of federal support, states and industry will need to organize funding strategies.

Furthermore, a coordinated approach to updating specifications and guidelines is necessary for aligning use of new types of cement and concrete nationwide. Federal agencies like the FHWA and NCHRP could play a leading role by developing model specifications, while regional centers and state DOTs adapt these guidelines to local conditions. If federal assistance is not available, states will need to join forces between themselves and with industry, and potentially large local agencies, to move forward.

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Data Summary

Products of Research

The product of this research is three documents: Deliverable 1A, a literature review report; Deliverable 1B, a summary table document; and Deliverable 3, the final report.

Data Format and Content

This project did not generate new data in the sense of experimental or empirical data. Instead, it involved gathering information from the literature. The list of used references was provided with each deliverable.

Data Access and Sharing

The bibliography accompanies each of the submitted reports in this project.

Reuse and Redistribution

All cited references are publicly available through publicly available websites and academic journals.

Appendix

Demonstration of the Use of Wood Ash as SCM in Concrete

Step 1A: Lab scale (mortar scale):

- Work with the suppliers to collect the materials and their associated safety data sheets. Sign any material transfer requirements.
- Identify relevant standards (ASTM, ACI, AASHTO, etc.) or non-standard test procedures or develop new test procedures if needed.
- Characterize basic chemical and physical properties.
- Perform testing and generate initial engineering performance data.
    - Physical and chemical properties
    - Pozzolanic reactivity
    - Alkali-silica reaction (ASR)
    - Sulfate attack
    - Foam index test
    - Soundness
- Make recommendations for the next step if the results warrant advancement.
    - Select ash candidates for concrete testing

Step 1B: Lab scale (concrete scale):

- Engineering performance assessment:
    - Collect materials and SDS from supplier, confirm physical and chemical properties again if a new source or batch,
    - Identify relevant standards for essential concrete testing (ASTM, ACI, AASHTO, etc.) and develop new performance-based test procedures if needed.
    - Characterize concrete fresh and hardened properties:
    - Assess the workability, finishability, setting, and curing requirements of the concrete.
- Initial cost estimates:
    - Estimates of cost of transportation
    - Estimates of costs of laboratory certification or any milling, sieving, and drying needed

- Scalability:
    - Feedstock types, properties, and processing
    - Combustion method
    - Seasonal availability
    - Current uses
    - Treatment processes needed: milling, drying, sieving, and others
- Supply chain and transport
    - Distance and modes of transport to cement or concrete plants
- Document, then Clearly Communicate: Perform the actions outlined in Section 6.2.1 appropriate for the stage
    - Communicating results directly to the supplier (innovator) to address any issues identified, optimize or customize the technology for the application, and prepare for the next stage.
    - Writing annual (or semi-annual) technical reports that summarize the results of testing and evaluation, including assessments and any additional work needed to advance to the next step.
    - Present the results to stakeholders via webinars or at industry and technical conferences
- Make recommendations for the next step if the results warrant advancement.
    - Select candidates for slab construction

Step 2: Slab scale (no structural load):

- Engineering performance assessment based on a 3-slab construction:
    - Collect one or several tons (often delivered in super sacks) of wood ash from the biomass plants with the SDS.
    - Confirm the physical and chemical properties of the received ashes at this production scale.
        - Particle size
        - Chemical composition
        - Carbon content (LOI)
    - Identify candidate project locations: sidewalks, walk or bike paths, streets on the UC Davis campus, or at UCPRC facilities location.
    - Coordinate with a local ready-mix concrete producer for production and delivery.
        - Deliver the ash to the local concrete producer,
        - Concrete producers may need to test small trial batches or pour a test pad

        - Assess compatibility with the admixtures used by the concrete producer
    - Coordinate with a local contractor to perform placement and finishing
    - Procure instrumentation and data acquisition system
        - Strain gages to monitor volumetric changes, relative humidity, and temperature sensors to monitor:
            - Uniform shrinkage/expansion
            - Curling and warping from nonuniform temperature and drying shrinkage across slab depth
    - Build slabs and assess constructability.
        - Build another set of 3 slabs on the same day (same climatic conditions) with cement (OPC or PLC) only or a traditional SCM like coal fly ash or slag.
    - Instrument the slabs for environmental monitoring.
    - Assess compatibility with other concrete components, including admixtures, during mixing, transport, placement, finishing, and curing.
    - Assess hardened properties of concrete:
    - Evaluate production concrete performance: strength, durability, and other key properties depending on application.
    - Cast specimens from the delivered concrete
        - Compressive and flexural strength with age
        - Modulus of elasticity with age
        - Drying shrinkage with age
    - Monitor the mid-term and long-term behavior of the material in the field in various climate conditions.
        - Analyze temperature, relative humidity, and strain data from the slabs and determine the curling and warping magnitudes in the slabs and compare those to the control slabs
    - Round-robin testing and variability confirmation: repeat the same three-slab construction and testing frame in different climate areas (wet-freeze, dry-freeze, dry-no-freeze, wet-no-freeze) at satellite centers (could be done at the same time if feasible/appropriate) where the technology may be applicable.
- Cost and market competitive assessment: Identify the initial cost of ash
    - If any treatments needed, like ball milling, will be added cost both capital costs for a large milling and screening facility and operational costs
    - Third-party laboratory certification will be an added cost

- Environmental performance assessment: Producer should be collecting the necessary data to generate an EPD at this stage.
    - The environmental impacts of wood ashes (A1-A3) from biomass plants mainly involve any treatment that may be necessary, such as milling, drying, etc.
- Scalability assessment: Assess the availability of raw materials, chemicals, fuels, and other resources required for production.
    - Identify bottlenecks in production and ways to remove them, such as grinding certification.
    - Determine if the technology displaces any existing use paths or processes and compare environmental impacts with those existing processes.
        - Wood bottom ash is used as the road base layer.
        - Wood fly ash does not have an added-value use.
    - Support supply chain development and reliability: Evaluate proximity and access to transportation modes, i.e., rail and freight.
- Document, then Clearly Communicate: perform the actions outlined in Section 6.2.1 appropriate for the stage
- Codes and standards.
    - Develop new non-standard special provisions and identify changes in design information, standard specifications, or standard special provisions and codes that would need to be made for pilot scale implementation.
    - Produce draft versions of those documents necessary for pilot use for industry and agencies to review.
- Celebrating success and building momentum: repeat the steps as outlined in Section 6.2.1
    - Hold open house events to showcase construction
    - Distribute educational videos of construction with wood ash concrete
- Prepare for the next step, if warranted by results

Step 3: Pilot scale (with structural load):

- Engineering performance assessment: Identify a pilot project in coordination with local or state road agencies or regional centers with accelerated loading capabilities. These could include State DOTs' stationary heavy vehicle simulators, such as the one at UCPRC in Davis, CA
    - Test tracks such as MnROAD in Minnesota or NCAT track in Alabama
    - Mainline pilot test sections: sections embedded in construction projects on mainline highways or streets

- Help local government or private owners apply for grants: AID, SHRP, LCTM, and state and federal programs available for implementation and sustainable practices.
    - Confirm the chemical/physical properties at scale production.
    - Repeat steps for engineering performance evaluation in the Slab scale.
    - Continue to collect data from demonstration projects
- Environmental performance assessment: centers collect an EPD for the material from the supplier. This should be a requirement at this stage.
- Document, then clearly communicate: repeat the steps as appropriate for this stage as outlined in Section 6.2.1
- From knowledge to know-how: developing training resources: repeat steps as appropriate for this stage as outlined in Section 6.2.1
- Celebrating success and building momentum: repeat the steps as outlined in Section 6.2.1
- Scalability and supply chain established
    - The supplier has performed a supply-demand analysis and is prepared to scale production to support identified markets.
    - The supplier has secured supplies of raw materials with economical transport modes (rail, barge, truck)
    - Distribution networks (cement plants or concrete producers) are established through partnerships with third-party logistics providers. Regional distributors or storage facilities may be needed.
- Cost analysis, market demand, and price benchmarking: the supplier performs technoeconomic analysis for plant production and establishes the cost of material at this scale and expectations for cost reductions at full scale.
    - The supplier works on assessing market competition, break-even study to establish profit margins, and sensitivity analysis to determine price and calculate the timeline of return on investments.
- Prepare for full-scale implementation if warranted by results

Step 4: Standard practice

- Support implementing agencies with the knowledge, data, and expertise needed to update their specifications, codes, and design practices, include them in technical guidance and consider them in the asset management system to go from Pilot2StandardPractice.
- Documentation and Clear Communication: Effective documentation and communication are vital to ensure that stakeholders understand and accept the new practices following the steps outlined in Section 6.2.1.

- From knowledge to know-how: developing training resources: repeat steps as appropriate for this stage as outlined in Section 6.2.1. The centers will:
    - Develop Customized Training Documents: Create training materials tailored to different stakeholder groups: inspectors, contractors, and regulatory bodies, addressing their needs and concerns.
    - Collaboration with Regulatory and Standards Bodies: Work closely with regulatory bodies and standards organizations (e.g., American Concrete Institute) to ensure provisions for the materials are included in relevant codes and standards. This process may involve submitting data, research findings, and case studies to validate the technology and demonstrate its performance in real-world applications.
    - Incorporation into Specifications: Support the integration of the technology into material and construction specifications, ensuring that it becomes a recognized and standardized option for various applications.
    - Integration into Design Manuals, Catalogs, and Tables: Facilitate the inclusion of the technology in design resources such as manuals, catalogs, and tables, making it accessible and convenient for practitioners to use in routine design and planning.
    - Training and Professional Development: Offer targeted training through short courses, workshops, and seminars to enhance stakeholders' understanding and capability in implementing the new technology. These sessions may cover best practices, troubleshooting, and compliance with updated codes and specifications.
    - Laboratory Equipment Upgrades: Assess and, if necessary, upgrade laboratory equipment to accommodate verification testing of the new technology, ensuring that testing facilities are equipped to support reliable quality control and compliance