MIT CONCRETE SUSTAINABILITY HUB

CSHub Annual Report

An Overview of CSHub Research and Activities in 2021

March 2022

The MIT Media Lab was desgned by the ronowned architect Fumihiko Maki. Photo: MIT Image Library

Three Goals. One Solution.

MIT CONCRETE SUSTAINABILITY HUB

Concrete is foundational to civilization. And it will remain foundational to its future—especially as climate change transforms our built environment.

We at CSHub are parsing these transformations—and concrete's role in them—through the lens of three objectives: realizing carbon neutrality, building world-class infrastructure with finite resources, and creating cities resilient to the stresses of climate change.

In 2021, we relentlessly pursued these objectives. We outlined in high-impact journals how concrete production and use could decarbonize key sectors; modeled how concrete could produce cities resilient to extreme heat; and presented new strategies to improve paving performance and environmental outcomes across the U.S.

Underlying this work is an awareness that concrete must never be viewed in isolation. Its key properties imbue it with life cycle impacts that transcend the scope of any single project. For us to attain carbon neutrality, these well-established impacts must inform today's decision-making.

To build this bridge between knowledge and implementation, we elevate our work through active outreach. Our leadership routinely promotes our research in world-class media outlets, internationally reputed conferences and events, and our own widely attended webinar series.

That research is as interdisciplinary as it is collaborative. Through collaboration with industry, we stay abreast of challenges and trends to hone a diverse portfolio of work that supports ambitious carbon neutrality objectives. Coalition building is key for us. We also enlist the guidance of crucial audiences, including policymakers, journalists, academics, and businesses. When solutions to climate change demand a systems perspective, it's only through consensus that we can succeed.

But even as new solutions generate tectonic shifts, one thing will remain constant: the utility of concrete. This is not to say concrete will remain unchanged. Innovations in its design and application will reshape the material just as it reshapes the nature of sustainability. As an active contributor to this exciting and essential process, **we invite you to join us in shaping and reshaping this indispensable material.**

Dr. Randolph Kirchain
Director
The MIT Concrete Sustainability Hub

77 Massachusetts Ave, 1-372, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

2021 in Numbers

Research

10 Journal papers, including one in the *Proceedings of the National Academy of Sciences*

8 Research briefs

Audiovisual

6 Webinars, 1,340 attendees

2 Explainer videos, including one presenting an overview of CSHub research and activities

23,000 YouTube views

Photo: MIT Image Library

Presentations

32 Presentations

3700+ Attendees

Highlights include World Bank Circular Economy Forum and TRB Annual Meeting

Media Coverage

10 Appearances in national news outlets

5 Op-eds, including in *The Hill*

3 Video interviews with media outlets, including Reuters and CBS

Realizing Carbon Neutrality

In 2021, MIT CSHub researchers sought to address an essential but intricate challenge: how do we cut concrete's emissions as its use increases? Our research, published in high-impact journals, identified holistic interventions to dramatically slash the emissions of concrete and its key applications—even as concrete use accelerates.

Proceeding Forward

Much like the vehicles that drive on it, a pavement exerts an impact on its surroundings: It can change vehicle efficiency, augment building energy consumption, and even moderate air temperatures. Paving a carbon-neutral road network will therefore mean devising interventions to both concrete's production and its use in the built environment

In a paper in a preeminent journal, The *Proceedings of the National Academy of Sciences (PNAS)*, CSHub researchers cataloged the myriad impacts from the U.S. pavements and building sectors—including those from concrete usage. By plotting several interventions, including the use of low-carbon concrete mixtures and optimization of concrete use, they then estimated how potential reductions to both sectors could contribute to climate targets. The results of their analysis showed immense opportunities.

Under their most ambitious scenario, the emissions for pavements and buildings between 2016 and 2050 could fall by up to 65 percent and 57 percent, respectively—even if concrete use were to triple over that same period. Most significantly, the team found that most emissions during the analysis came not from materials and construction, but rather from operational energy consumption.

The PNAS paper offers far more than outcomes. Its exhaustive forecasting should provide policymakers, government officials, and other scholars a clear roadmap to guide their decisions and investigations. It also delivers a call to action: Carbon neutrality is possible and, when using the right tools and perspectives, attainable.

Carbonation Questions

To most, the word 'carbonation' evokes refreshment—not infrastructure. But besides a soda's fizz, the term denotes an intrinsic property of concrete. A natural process of carbon uptake, 'carbonation' refers to the reaction of CO_2 in the atmosphere with the calcium hydroxide along concrete's exposed surface. While the byproduct of carbonation, calcium carbonate, is negligible, the reaction has profound consequences for our infrastructure and the climate.

Concrete pavements, due to their immense exposure to air, have a significant potential for carbonation and, as a result, CO_2 sequestration. But the amount of CO_2 concrete pavements can actually capture has remained up in the air—until now.

A study by CSHub researchers in Resources, Conservation and Recycling sought to ground this question of carbon uptake in a comprehensive study. By modeling exposed pavement surface area, expected maintenance actions, and paving budgets across the entire U.S. pavement network, the team produced one of the first high-resolution estimates of pavement carbonation nationwide. In total, they found carbonation could offset around 5% of the emissions associated with cement production for all U.S. concrete pavements

Spreading the Word

In addition to producing robust research, CSHub has sought to actively place its work in the broader discussion. Through media coverage, webinars, and public presentations the team has sought to provide decision-makers access to cutting-edge findings that can enhance the nation's approach to infrastructure sustainability.

The CSHub webinar series has, in particular, helped inform thousands of global thought leaders on the issue of carbon-neutral concrete. Our webinars on this topic set attendance records in 2021 and engaged members of critical organizations in civil society, engineering, academia, business, and government. Regularly in attendance webinars were officials from state and city DOTs, Fortune 500 companies, and global top ten research institutions.

Our presentation schedule took us far beyond our usual webinar audience series. We also gave presentations to global leaders at the American Institute of Architects, The World Bank, and MIT World Real Estate Forum. In total, more than three thousand were in attendance to hear us speak on the topics of low-carbon concrete and carbon neutrality.

The global conversation around carbon neutrality is overdue—and still in its infancy. At CSHub we realize the importance of engaging in these essential discussions at such a nascent stage. In 2021, our research allowed us to define the discussion and our communications initiatives brought us to its forefront.

Since its completion in 1916, the Great Dome has come to represent the Institute. Photo: MIT Image Library

Resilient Cities

The MIT campus along Memorial Drive. CSHub is modelling precipitation floods along this iconic but flood-prone thoroughfare. Photo: MIT Image Library

Resilience and sustainability are often treated as distinct concepts. At CSHub, however, we see them as part and parcel. We've found that the enduring economic, environmental, and social viability of our built environment depends on long-term perspectives that ensure success well into the future. In short, to sustain our most essential systems, we need to build them resiliently.

The New Sustainability

To mitigate climate change humanity needs to dramatically reduce its building emissions. But to cope with extreme weather and rapid urbanization, it will also have to build more—and more resiliently.

In an op-ed in *The Hill*, CSHub's principal investigators Franz-Josef Ulm and Randolph Kirchain sought to resolve this apparent tension. Drawing on over a decade of research, they explained that resilient construction doesn't necessarily entail more emissions. In fact, they explained, resilient materials like concrete can offer life cycle emissions benefits.

They cited CSHub research and explained that resilient materials like concrete can offer numerous sustainability benefits. In the case of pavements, the right materials can limit excess fuel consumption in vehicles, preclude emissions from frequent maintenance and even lower air temperatures and energy consumption in cities.

But resilience also can apply to spending: selecting optimal materials can reduce future uncertainties in cost and deterioration, which, in turn, can ensure lower costs well into the future.

Resilience, they argued, is much more than durable construction. It's a question inseparable from sustainability: how will we build our systems to last more than just a lifetime?

Model Structures

How can we tell if a building will survive a hazard that has yet to occur? CSHub uses simulations—tens of thousands of them—to find the answer. Our researchers have developed novel,

77 Massachusetts Ave, 1-374, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

streamlined tools for simulating hazard damage in structures and communities. As existing simulation techniques remain resource-intensive, we prioritize computational efficiency to make hazard modelling more accessible.

In 2021, the CSHub resilience team conducted simulations at scales spanning single components to entire cities. Their work provided insights into wind, fire, seismic, flooding hazards to guide better policies in the most hazard-prone of regions.

Dr. Talal Mulla's work focused on these smallest of these scales: structural and non-structural components. His research centers on a tool known as the fragility curve. As a way of representing the likelihood of damage at a given hazard intensity, fragility curves have become an essential resilience tool. But since they are often calculated for each building component, they can also prove impractical.

To overcome this issue, Dr. Mulla has developed a new method for readily integrating many component-level curves into a single building-level curve. He applied this method to a case study of wind loading on three five-story structures: wood without a core, a wood structure with a core, and a reinforced concrete structure. Those with greater reinforcement possessed greater resilience, with the concrete structure demonstrating the strongest results.

As he advanced his fragility curve research, Mulla relied on the work of CSHub researchers Tina Vartziotis and Kostas Keremidis. The two spent much of 2021 honing a molecular dynamics (MD) model for simulating building failure. Rather than considering a building as an ensemble of elements, the MD model models structures as an ensemble of "atoms". Inspired by physics, these atoms interact much via forces and moments, much like the bonds in molecules.

Vartziotis and Keremidis applied this approach to model complex structural elements like sheer walls in the face of several hazards. They conducted a case study of three typical structures: a reinforced concrete design with sheer walls, a concrete beam-column design, and a wood design with sheer walls. They then subjected these designs to three major hazards: fire, earthquake, and wind. Their case study indicated that concrete structures with sheer walls had the greatest performance—and in the case of fire, would mitigate failure entirely.

When most people think of hurricanes, high winds often spring to mind. Flooding, however, occurs concurrently—and generates significant

77 Massachusetts Ave, 1-374, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

CSHub research assistant Bensu Manav is passionate about the intersection of hazard resilience and social vulnerability.

losses. Flood modeling is not up to the task of mitigating these losses. As floods depend on numerous factors—topography, climate, geology, infrastructure—predicting their extent has proven difficult.

Elli Vartziotis, a PhD candidate at CSHub, is applying statistical physics tools to clarify the precipitation flood modeling process. Her model relies on density-functional theory (DFT), which was developed to study the porous space by measuring absorption and desorption in porous materials. In her work, DFT helps model flooding and drainage in a 3D environment. Due to its computational elegance, it has the potential to produce more detailed results, more quickly.

Social Vulnerablity is Structural

Resilience isn't just structural—it's also social. Factors like age, race, income, and health status frequently contribute to a household's response to and recovery from a hazard. And yet, social factors still often fall outside the scope of conventional engineering practice.

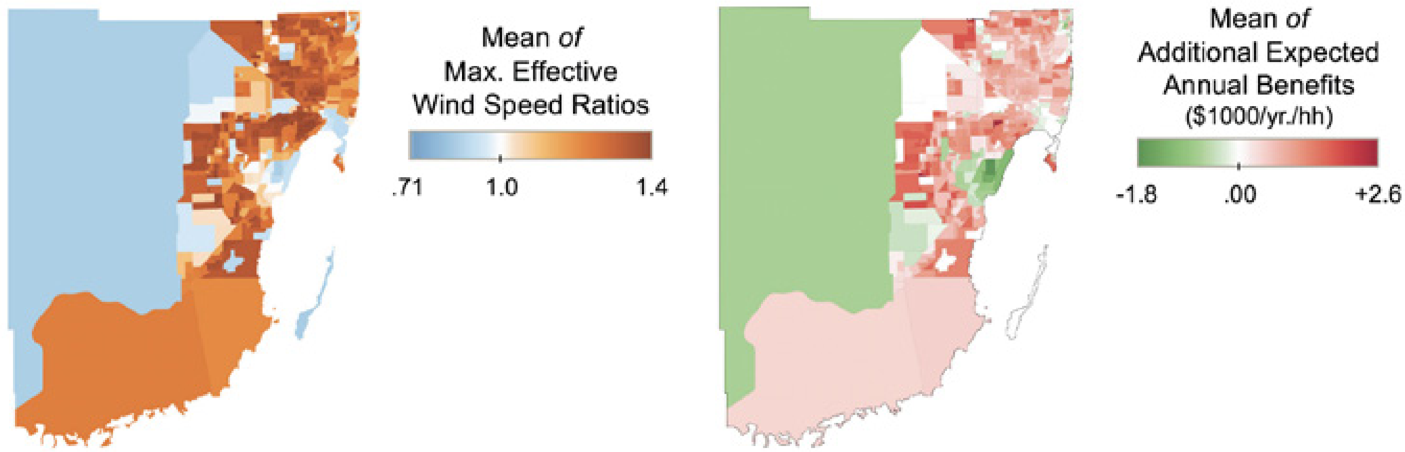
CSHub Ph.D. candidate Bensu Manav hopes to change this by investigating the intersection of climate, engineering, and equity. In an August 2021 MIT News profile, she explained her interest in the subject and detailed the changing landscape of resilience engineering.

Growing up in two hazard-prone regions—Miami, Florida and Istanbul, Turkey—Manav studied engineering in part to keep natural hazards at bay. Yet, her time at CSHub has reshaped her understanding of resilience and engineering. Rather than seeking to "tame nature", she learned the importance of adaptation: how can households prepare for an inevitable hazard? Will they have the means to cope with the losses they'll likely experience? The issue of social vulnerability is central to these questions.

Without, for instance, the financial means or the mobility to cope with a hazard, socially vulnerable residents may experience the same hazard in starkly disproportional terms. By tracking the relationship between socioeconomic characteristics and hazard losses, Manav hopes to provide a new framework for introducing more resilient construction into vulnerable communities.

Avenues for Resilience

Resilience isn't just a response to physically destructive hazards like forest fires and hurricanes. It



By applying CSHub's city texture modeling approach, research assistant Bensu Manav has identified gaps in conventional loss estimation tools. The figures above show how modeling urban layouts captures wind load amplifications (wind speed ratios) and potential annual savings if city texture informed mitigation.

also involves preparing for less visible but equally acute climate challenges, like extreme heat.

As the world urbanizes, more and more people will experience elevated air temperatures due to heat islands and climate change. And while urbanization will continue to accelerate, it's still possible for cities to moderate extreme heat. One solution is through their pavement networks.

In a paper published in *Environmental Science & Technology*, CSHub researchers Randolph Kirchain, Hessam AzariJafari, and CSHub alumni Jeremy Gregory and Xin Xu presented a comprehensive model for all of the climate change impacts of cool pavements in Boston and Phoenix.

They found that the use of cool, concrete pavements would offer myriad climate benefits to both cities. These benefits came in the form of lower summer temperatures—Phoenix and Boston would see reductions of 4°F and 3°F, respectively—as well as greenhouse gas reductions. By offering smoother, more durable paving surfaces, concrete could reduce vehicle excess fuel consumption while its greater reflectivity could reduce energy consumption in nearby structures. In total, both cities saw significant decreases in emissions over the analysis period, with Boston seeing as much as a 3% reduction.

These findings proved popular with the public, the media, and policymakers. They served as the basis for two op-eds, one in *The Conversation* that was republished in *Fast Company*, and *The Daily Beast* and another in *The Boston Globe*. The latter culminated in a meeting with local officials to discuss the state of urban heat in Greater Boston.

Sustainable Infrastructure

With the passing of the Infrastructure Investment and Jobs Act, the U.S.'s chronically underfunded infrastructure will receive much-needed investment. But to ensure that that investment translates into better outcomes will require an entirely new perspective. Our work in 2021 positioned us to supply that perspective.

From Source to Surface

Effective infrastructure spending is only possible with adequate data to inform it. Unfortunately, most transportation agencies lack access to the road quality data they need to make the most informed planning decisions. CSHub and the University of Massachusetts Dartmouth have developed the Carbin app to crowdsource this essential data.

While Carbin's crowdsourcing success has already been established, CSHub sought to deepen the app's utility and rigor. In a paper in the *Proceedings of the Royal Society A*, the Carbin team detailed the scientific mechanisms of their app.

They outlined the foundation of their approach: the quarter-car model. To process raw vehicle acceleration measurements, the team mapped them onto a representation of a single wheel and suspension system of a moving vehicle. This, they explained, allowed them to estimate suspension travel and, consequently, the roughness metrics of the road below.

In a subsequent paper, CCSHub research assistant Meshkat Botshekan explored a new potential application for Carbin: streamlined traffic measurement. Through a physics-based approach, Botshekan investigated how to extrapolate broader traffic properties, including traffic density, from the measurements of a single vehicle. He validated his model using two case studies—one of Greater Boston and another from the German A1 Autobahn—that featured real-world traffic measurements. In both cases, his model proved in agreement with the two real-world scenarios.

These encouraging findings are establishing Carbin as a state-of-the-art alternative to outdated modes of data collection. And with the nation embarking on immense infrastructure investment, such an alternative will prove crucial. DOTs will need sufficient data to ensure measurable improvements in performance and sustainability.

77 Massachusetts Ave, 1-374, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

Carbin can offer the real-time information necessaray to inform their many upcoming decisions.

Building Lifetimes

The building sector generates roughly 40% of the world's greenhouse gas emissions. And cutting its footprint will be no simple task. Designers must account for the initial footprint of building materials as well as their impact on a structure's operational emissions. The challenge, then, is to tally these many impacts before material choices are made.

CSHub researcher Jingyi Liu addressed this critical climate and design issue by advancing an innovative LCA tool for architects. The success of Liu's tool is in its flexibility. Rather than recommending specific design attributes, Liu's LCA tool provides a range of optimal and quasi-optimal values that allows users to balance cost, environmental impact, and design diversity.

This flexibility could allow architects to maximize the crucial materials selection stage. By better helping balance design and performance priorities, this tool could ground aesthetic decisions in scientifically rigorous modeling outcomes. And these outcomes are promising: She found that her model could help save 10% on cost and 20% on the carbon impact on average. For a medium-sized office building, these savings could total $6 million over 50 years.

Paving Futures

As infrastructure must last many decades, planning sustainably demands long-term perspectives. Dr. Fengdi Guo, a recent CSHub alumnus, spent his tenure at CSHub modeling pavement networks over numerous decades to optimize their sustainability. His work elevates a crucial but complex element of the planning process: uncertainty.

Future uncertainties in deterioration and material cost all complicate asset management. Given the challenges associated with predicting them, though, many agencies disregard them entirely. Dr. Guo, however, has found that cost-effective, sustainable pavement networks depend on embracing uncertainty. He has perfected a pavement treatment path dependence (PTPD) model that suggests the optimal paving decisions over many decades based on each outcome in uncertainty.

In a paper published in *Transportation Research Part D*, he applied his new PTPD model to a case study of the Iowa U.S. Route network. His analysis found that the PTPD approach

Meshkat Botshekan has helped develop Carbin, a crowd-sourcing app produced jointly by CSHub and the University of Massachussetts Dartmouth.

combined with three paving management strategies—a mix of materials, decision-making flexibility, and a long-term planning horizon—could significantly improve asset management outcomes. Over the 30-year analysis period, this combined approach would cut pavement network emissions by 20% while improving performance by 32 percent—all without increasing paving budgets.

While originally intended to help DOTs do more with less, this approach can also guide them through the nation's upcoming infrastructure investment. With substantial funds on the line, fine-tuning investment is essential. Today, 'doing more with less' is no longer the issue. The question, instead, is "how can we do more with more"? The latest asset management tools, like PTPD, offer a promising answer.

An Opportune Opinion

CSHub stands apart through its commitment to both research and implementation—ensuring that our findings define as well as shape sustainable planning decisions.

In 2021, CSHub advanced this commitment through several communications initiatives, which included appearances in prominent media outlets and at internationally attended venues.

While policymakers debated the role of infrastructure investment, CSHub's past executive director, Jeremy Gregory, penned an op-ed in *The Hill*. His thesis was that to build sustainably we need to consider the very definition of 'sustainability'.

Far from being a buzzword, wrote Gregory, 'sustainability' has a concise yet versatile definition: building our systems to last. In the face of climate change, that entails building lower-emitting infrastructure, but it also involves building resiliently and economically to endure more intense hazards and financial shifts.

Gregory explained that these three dimensions—environmental, functional, and fiscal—reinforce each other. Resilient infrastructure, for instance, not only protects from the havoc of climate change, but also mitigates economic losses and reconstruction emissions. In this sense, sustainability is less a set of criteria but more of a fundamental perspective that can and should guide all decisions.

Our research represents just a portion of the rich array of infrastructure science work at MIT. To coalition-build and present more holistic, integrated solutions, we collaborated with Drs. Jinhua Zhao and Anson Steward the MIT Mobility Initiative to produce a joint op-ed. The final piece, also published in *The Hill*, responded to a critical question for Capitol Hill at the time: "How much do we spend on infrastructure?".

While the authors endorsed robust spending, they also posed an equally critical question: "How should we spend?". They argued that the approaches used to allocate spending will ultimately prove as decisive as the magnitude. To sharpen spending, they advocated for long-term, systems perspectives. These included life cycle assessments of infrastructure decisions and accessibility-informed planning—both bolstered by extensive data collection. The urgent demand for these approaches, the authors wrote, necessitated a new narrative to guide our spending: "We need to understand that spending boldly is just the first step: ultimately, we must spend shrewdly as well."

The piece proved a success. Not only did it generate discussions with senior DOT officials and respected transportation experts, it also cultivated fruitful cross-departmental connections at MIT—connections that promise further opportunities for outreach and engagement.

Electric at All Scales

At CSHub, we model how concrete shapes the future. But we're also shaping the future of concrete. Researchers Drs. Asheesh Shukla, Nancy Soliman, and Nicolas Chanut have dedicated themselves to developing a new form of cement and concrete. Rather than a purely structural material, their innovative nanocarbon-doped cement mixture will introduce new functionalities.

Leveraging the high conductivity, availability, and affordability of nanocarbon black, the team has developed a cement that can carry current—and reshape construction. They have spent the last two years calibrating these conductive mixtures, testing their conductivity and mechanical properties as a function of nanocarbon black content and dispersion.

Conductive concrete would enable simple slab heating and provide the basis for deicing streets. Moreover, it could turn concrete into a conduit for cleaner energy. As the grid transitions to more intermittent sources of power, conductive concrete could also allow structures to store excess renewable energy to soften the new grid's intermittency.

The upshot of this multifunctionality is improved sustainability, as it allows concrete to yield even greater lifetime returns at the same initial investment. Through adjustments in mixtures and constituents—both radical and subtle—it's possible to continuously reinvent this already infinitely versatile material.

Photo: MIT Image Library

2022: The Next is Now

When entering a new year, it's natural to ask, "What's next"? At CSHub, we ask that question every single day.

As you've seen, our work deals chiefly with the future—how to predict it, and most importantly, manage it. What it's taught us is that the next is now: Each decision we make has lasting impacts that demand deep consideration today.

Our research portfolio is no exception. Over the past year we've thought carefully about what's next in the broader sphere of sustainability. We've identified one pressing challenge: attaining carbon neutral concrete will depend on accounting practices that are still in their infancy.

In the coming year, we'll be enhancing our life cycle analysis tools—already some of the world's most comprehensive—to create a holistic cradle-to-grave system for accounting and reporting concrete's emissions. Such a model will help realize carbon-neutral concrete by tracking the entirety of the material's impacts—including those it has and will continue to mitigate.

The aim of such a tool is, of course, is to illuminate the target of carbon neutrality. And while defining and fulfilling ambitious targets is daunting, it's something we've grown to appreciate as we continuously model the future. To us, it's both a scientific and introspective process: a way of defining who we are, who we'll be, and, most importantly, what we value.

We believe our work in 2021 was a demonstration of these values—collaboration, curiosity, rigor, and foresight. **Thank you to everyone who helped us along the way with your guidance and expertise. We welcome a new year and your ongoing support.**

Dr. Franz-Josef Ulm
Faculty Director
The MIT Concrete Sustainability Hub

77 Massachusetts Ave, 1-372, Cambridge, MA 02139 | cshub@mit.edu | cshub.mit.edu

CSHub

MIT
CONCRETE
SUSTAINABILITY
HUB

March 2022