# Spring '23–'24 Review

MIT CSHub

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# Carbon Neutrality

*The MIT CSHub is working to understand and amplify the life cycle benefits of concrete while exploring existing and novel solutions to realizing a carbon neutral industry. Over the past year, the CSHub published extensively on topics such as natural and forced carbonation, natural hazard resilience, and even conductive concrete.*

## Multifunctional concrete: A new frontier to reduce or offset concrete’s footprint

The most exciting findings often begin with a small proof of concept: Late into the night of May 5th, 2023, research scientist Damian Stefaniuk observed something that demonstrated that the seemingly improbable invention of the team led by Franz-Josef Ulm and Admir Masic was very possible.

Wired up to a “battery” made of stacked discs of carbon black-doped concrete soaked in electrolyte, a small LED light started to glow. The supercapacitor had been charged up with a small solar panel, and the light stayed on even when the power source was disconnected. Ulm and team had stored and discharged energy within concrete by creating a conductive carbon network within it.

> *The principal sources of renewable energy, wind, solar, and tidal power, all produce their output at variable times that do not correspond to the peaks in electricity usage, so ways of storing that power are essential.*
>
> *Existing batteries are too expensive and mostly rely on materials such as lithium, whose supply is limited, so cheaper alternatives are badly needed. “That’s where our technology is extremely promising, because concrete is ubiquitous,” said Professor Franz-Josef Ulm.*
>
> – MIT News: “MIT engineers create an energy-storing supercapacitor from ancient materials”

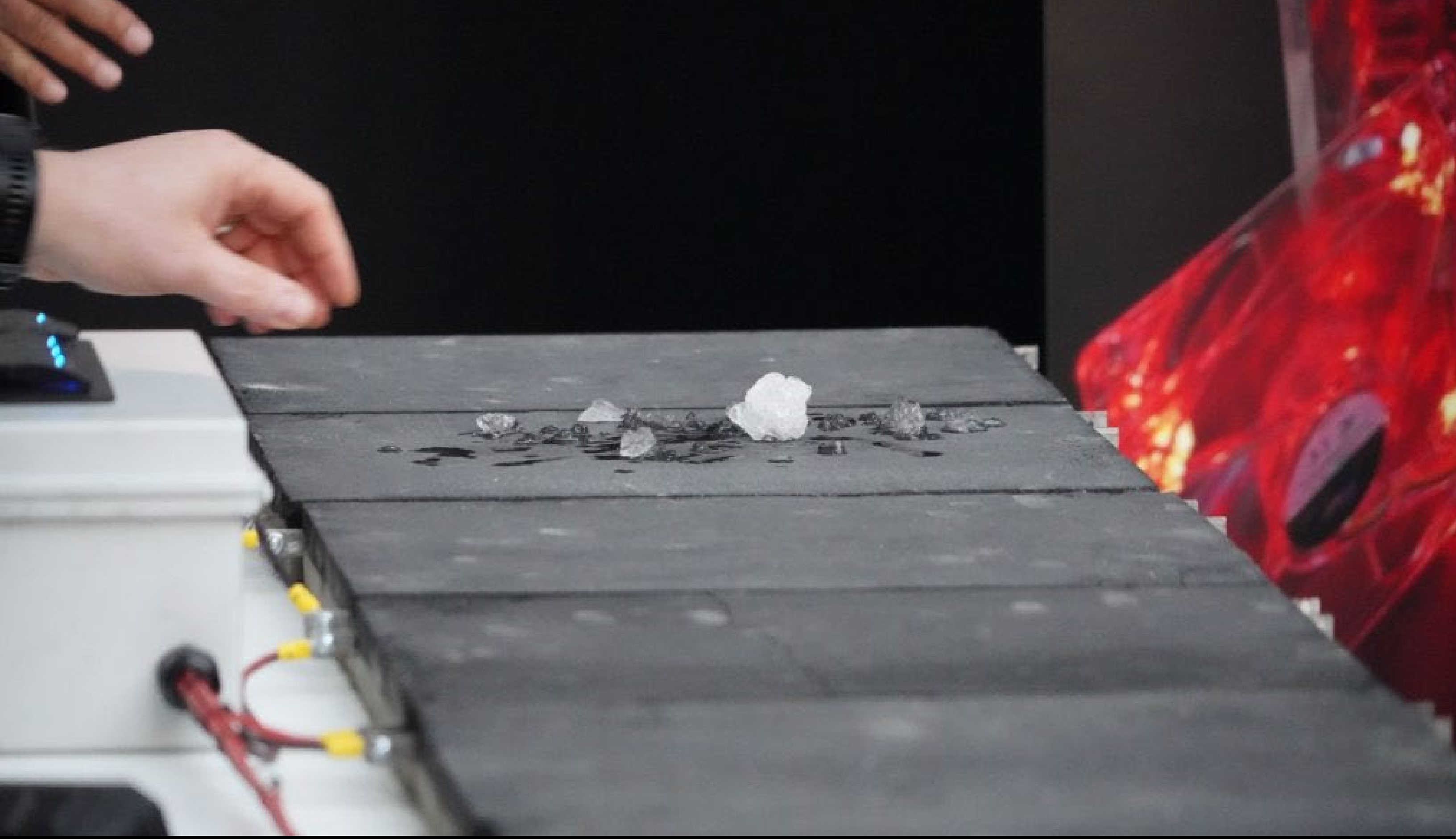
Within the span of a few months, the technology became capable of heating pavements and charging personal electronics. The researchers surmise that it could one day be made into conductive pavements that charge electric vehicles as they drive over them, “energy-autarkic” structures that can generate, store, and discharge power off the grid, and more.

For all the applications that could be in play, the technology was inspired by a simple idea: Extracting more uses out of the world’s most consumed building material – concrete. As such, it exemplifies the ethos of the CSHub in exploring ways to enable a carbon neutral industry through unconventional thinking.

Another emerging technology that has potential value in reducing concrete’s carbon footprint is **chemically-induced pre-cure carbonation** (CIPCC), investigated by CSHub Research Associate Marcin Hajduczek and team. In their research brief “Carbonation Before Curing: A New Path to Concrete Sustainability,” Hajduczek and Stefaniuk describe their method to introduce carbon dioxide into concrete mixes in a solid form (sodium bicarbonate crystals) rather than a gas as other methods have tended to do. Not only does this allow for the storage of a controlled and precise quantity of carbon dioxide in concrete, it boosts mechanical performance while theoretically boosting concrete’s carbon uptake capacity to offset at least 40% of emissions from the calcination of cement.

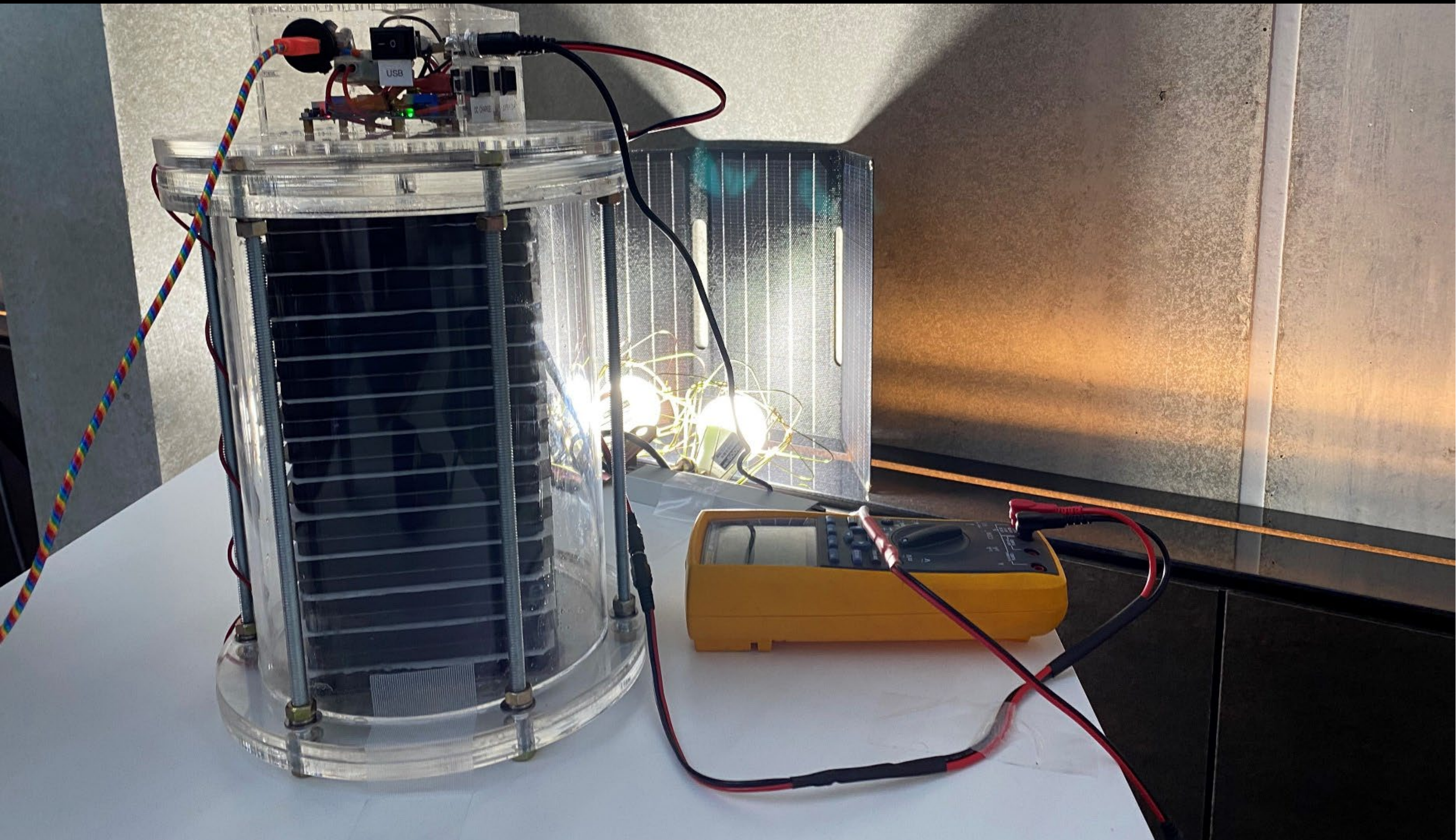
## How current solutions can enable a carbon-neutral industry today

Another piece of unconventional thinking: While much attention is being paid to emerging technologies to reduce concrete’s carbon footprint, the fact that ***carbon neutral concrete is possible today*** deserves equal attention.



***Top***: *Carbon black doped concrete pavements can have current run through them to heat their surfaces, allowing for deicing. If implemented for city roads and sidewalks, this technology could have benefits for pedestrian and vehicular safety.*

***Bottom***: *A charged carbon-cement supercapacitor powers multiple LED lights and is connected to a multimeter to measure the system's voltage at 12 volts.*



### *Leveraging carbon uptake*

One solution to lowering concrete’s carbon footprint is to take advantage of its ability to permanently sequester carbon dioxide via natural carbon uptake, a process which occurs during the use phase and end-of-life of cement-based products (CBPs). As detailed by AzariJafari in his interview for MIT News, “3 Questions: Leveraging carbon uptake to lower concrete’s carbon footprint,” carbon uptake is influenced by the climate, the types and properties of CBPs used, the composition of binders used, as well as the geometry and exposure condition of the structure. Carbon uptake is an essential part of the life cycle of CBPs and must be accounted for in carbon footprint calculations. As an example of carbon uptake’s significance, our analysis shows that the U.S. pavement network can sequester 5.8 million tons of carbon dioxide via uptake, over half of which will be sequestered when the demolished concrete is stockpiled at its end-of-life. Our Whole Life Cycle Carbon Uptake calculator enables construction stakeholders to estimate the carbon uptake of concrete structures during their use and end-of-life phases. Postdoctoral Associate Pranav Pradeep Kumar, a recent addition to the CSHub team, has made substantial progress investigating the carbon uptake for single-family and commercial building archetypes in an element-based, context-specific fashion.

Architects can amplify the impacts of uptake by designing to increase surface-to-area ratio (giving uptake a larger area on which to work), while concrete manufacturers can adjust binder type and quantity. Industrial ecologists and life cycle assessment practitioners should work to better quantify uptake’s impacts. For further information on our uptake research, see AzariJafari’s May 2023 webinar, “Carbon Uptake of Cement and Concrete Construction: From Single Element to National Level.”

### *Sustainability in concrete architecture*

On a similar note, the CSHub is working to understand how architectural design decisions can influence the embodied and operational impacts (other than uptake) of structures. In her October webinar, Hub alum Lucy Lyu explained how decisions like smaller column spacing; lower concrete strength for slabs, beams, and foundations; and lower primary-to-secondary span ratio can result in concrete structures with lower embodied carbon. The presentation also explored how concrete’s greater thermal mass than comparable materials (like wood) can result in energy savings for concrete structures.

The CSHub also began collaborating with the MIT Digital Structures Group, led by Professor Caitlin Mueller, which is investigating architectural design algorithms and tools to enhance concrete’s environmental performance. Some of the research in progress at the group includes 3D-printed formwork, structural optimization for beams and slabs, and generative structural design methods.

### *Enabling carbon capture, transport, and storage implementation at scale*

A new project underway at the CSHub investigates cost-effective strategies that can help the cement industry implement $CO_2$ capture, transport, and storage infrastructure at scale. Led by Research Scientist Elizabeth Moore, the project aims to characterize the costs associated with building out carbon capture infrastructure for the industry, including carbon pipeline infrastructure. Using spatial-economic optimization, Moore and team are exploring the possibility of creating a large-scale pipeline network based around the location of "carbon hubs" – collections of nearby industrial facilities (e.g., steel plants, power plants) which could make use of the pipeline at a lower cost. In granting pipeline – and therefore CCUS – access to other industries, the cement industry could have an outsized positive impact across sectors and accelerate industrial CCUS deployment.

### *AI in concrete research*

On a different topic, the CSHub is working to implement emerging artificial intelligence technologies into its work on sustainability. For instance, recent CSHub addition and Postdoctoral Associate Soroush Mahjoubi and Professor Elsa Olivetti are working to develop machine learning models capable of tasks like predicting the compressive strength of concrete with open-access datasets.

The above work on carbon neutrality demonstrates how the CSHub works to educate a range of stakeholders, from the general public to industry partners to policymakers, on the properties of concrete that make it a sustainable choice for building in many applications.

That is not to say, however, that there is not much work to be done in reducing the material’s carbon footprint. In the remainder of 2024, the CSHub is looking forward to demonstrating ways to further improve concrete’s environmental performance, whether through emerging technologies or better implementation of existing methods.

## Legislation and the future of concrete sustainability

The CSHub is also emerging as a thought leader on the topic of “Buy Clean” regulations to enforce or encourage the purchasing of lower-carbon materials. In the June 2023 op-ed in The Hill, “EPA must prioritize life-cycle emissions in building materials policy,” Randolph Kirchain and Hessam AzariJafari propose that the Environmental Protection Agency (EPA) should enhance its rules mandating the purchasing of materials with lower embodied carbon. As they explain, focusing on upfront emissions alone leaves carbon savings on the table. As a practical example, consider how electric vehicles (EVs) have a higher upfront carbon cost but frequently have lower lifecycle emissions. They challenge the EPA to develop a timeline to account for use phase and end-of-life emissions in their materials specifications.

In a similar vein, Hessam AzariJafari presented on “Concrete Material Transparency: How Buy Clean Initiatives are Transforming Project Requirements” at the American Concrete Institute’s Fall 2023 conference. Giving an example of why considering impacts across the life cycle is important, he explained how concrete pavements can improve fuel efficiency due to greater stiffness and smoothness, lower ambient temperatures due to higher reflectance, and naturally sequester carbon dioxide via carbon uptake.

The CSHub is also influencing other material emissions legislation. In October 2023, Randolph Kirchain spoke before the Massachusetts Senate Committee on Global Warming and Climate Change to deliver a presentation on reducing materials’ embodied carbon. He focused on why legislation should consider the importance of embodied emissions across the life cycle and how to drive supply chain innovation. Similarly, Kirchain participated in a special November briefing, “Concrete on the Hill Day,” at the Massachusetts Statehouse to present on the life cycle benefits of concrete, how its carbon footprint can be reduced, and how legislators can incentivize the construction industry to embrace it.

> *We could get halfway to (Massachusetts’) goal of net zero emissions today if we made changes to the formula. For instance, if we incorporate different binders (the cement or glue that holds the material together) and choose our aggregate (the rocks and sand used in the mix) correctly.*
>
> – Dr. Randolph Kirchain, South Coast Today: “Switching to concrete across construction industry could aid Mass. attain zero emissions”

# Infrastructure

*Infrastructure is the backbone of our society and economy. The CSHub has long investigated how to enable a pavement network with superior performance. Our computational tools and thought leadership emphasize that a life cycle approach to pavement network asset management is key to making smart investments.*

## On the path to reduce carbon emissions, don’t forget the roads

Roads form the backbone of our built environment. They take us to work or school, take goods to their destinations, and much more. The construction materials used in the U.S. pavement network, however, emit 11.9 to 13.3 megatons of greenhouse gases each year. This is equivalent to the emissions of a gasoline-powered car driving about 30 billion miles in a year.

Critically, 78% of pavement life cycle impact comes from the use phase, the most significant part of which is pavement-vehicle interaction (PVI): How roughness and stiffness impact the energy efficiency of vehicles driving over roads. The MIT CSHub is working to enable a more performant, lower carbon road network with fewer resources by considering PVI and other critical elements of the life cycle of roads.

### *Tools to quantify pavement environmental performance*

Essential to our approach is developing accessible tools for state Departments of Transportations (DOTs) and other government entities to quantify the impact of pavement performance improvements. In conjunction with the International Grooving and Grinding Association (IGGA), the CSHub released two such tools: The Fuel/Carbon Savings Calculator, which assesses how road smoothness improvements benefit fuel efficiency, and the Rigid Pavement Savings Calculator, which shows how more rigid pavements (like concrete pavements) improve fuel efficiency.

Another key tool being developed by the CSHub is the Streamlined Pavement LCA Tool. In December 2023, Haoran Li led a public webinar focused on the tool, which is intended to enable pavement design optimization and refine long-term performance forecasting. The approach accounts for enhanced maintenance and rehabilitation planning to mitigate greenhouse gas (GHG) emissions. Li explored his work during an open topic session at the Fall 2023 ACI conference, the title of his presentation was “Development of a streamlined framework for probabilistic and comparative life cycle assessment (LCA) of concrete pavements.”

Research Assistant Varsha Vaidyanath began work to develop a rating system for pavement environmental performance. As noted during her presentation “Benchmarking Pavement Environmental Performance Using Data-Driven Methods” during the Fall Advisory Meeting, Vaidyanath is working to compare road segment performance against benchmarks, assessing context-driven life cycle emissions to develop a scorecard for environmental performance.

### *Pavement sustainability advocacy*

In addition to developing these tools, we advocate for wise investments in solutions that boost the environmental performance of pavement networks. In the MIT News article “Study: Carbon-neutral pavements are possible by 2050, but rapid policy and industry action are needed,” we describe the results of a CSHub study which found that improvements ranging from using renewable energy for pavement operations to promoting paving materials diversity could allow the United States pavement network to be made carbon-neutral in the next three decades. Another critical finding is that nearly half of pavement network GHG savings can be achieved in the short term with a negative or nearly net-zero cost. In their January op-ed in The Hill, Randolph


*We can make demonstrable improvements to road ride quality and environmental footprint with **smart investments and long-term thinking**. For instance, by prioritizing concrete paving for high-volume traffic roads, we can keep important thoroughfares smoother and stiffer for longer. In our case study of Missouri, we could reduce GHG emissions by 8 percent by adopting this strategy.*

*In addition, when roads need maintenance, we should invest in treatment actions that will improve ride quality over the long term. More frequent road resurfacing and rehabilitation measures like diamond grinding are needed. Of similar importance, less frequent, long-lasting treatment like concrete overlays can provide long-term smoothness and dampen the negative impacts of deflection. Two examples created in a collaboration between the CSHub and the International Grooving and Grinding Association are the Fuel/Carbon Savings Calculator and the Rigid Pavement Savings Calculator.*

— Dr. Randolph Kirchain and Dr. Hessam AzariJafari, The Hill: "We're overhauling our cars in the name of energy efficiency – why not our roads?"

Kirchain and Hessam AzariJafari comment upon the Federal Highway Administration’s adoption of a performance measure giving state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) a way to track greenhouse gas emissions associated with transportation, particularly estimating highway tailpipe emissions and comparing them against a 2022 benchmark. While the measure traces the efficacy of initiatives to encourage greater fuel efficiency, electrification, and adoption of alternative transit modes, it overlooks the environmental impact of the performance of our road system. Noting that the use phase represents up to 78% of pavements’ life cycle impacts, Kirchain and AzariJafari encourage DOTs and MPOs to consider long-term materials decisions and road treatments to enhance road stiffness and smoothness, allowing vehicles to travel along them while expending less energy.

Similarly, Franz-Josef Ulm joined the 2024 Transportation Research Board Annual Meeting, attending a panel with U.S. Transportation Secretary Pete Buttigieg entitled “New Materials for Infrastructure: Reinventing the Roadway, Runway, & Railway.” The discussion centered on innovative durable materials, including green and low embodied carbon infrastructure materials, bio-engineered materials, and other topics related to decarbonizing the infrastructure supply chain.

### *What a single car can say about traffic (and road conditions)*

In another direction for our research on infrastructure, Postdoctoral Associate Meshkat Botshekan earned his PhD in September for his work, “Unveiling Roadway Network Safety: Application of Statistical Physics to Crowdsourced Velocity Data.” Dr. Botshekan investigated the risk of near-misses in traffic, finding that traffic density and velocity fluctuations forecast the risks of actual collisions. The work examined the reliability and resiliency of roadway networks at the state scale. His smartphone-enabled road condition monitoring system, in which users volunteer to have their acceleration and vibration data tracked while driving, reveals which road segments cause excessive fuel consumption due to their roughness. This research, based on the Carbin app, was funded in an earlier phase of CSHub’s work and continues to inform our current research. Dr. Botshekan’s work demonstrates that more resilient and durable road construction has an impact on both everyday traffic safety and network sustainability.


*CSHub’s Faculty Director, Professor Franz-Josef Ulm (rightmost), joins a TRB 2024 panel moderated by U.S. Transportation Secretary Pete Buttigieg (fourth from left).*

# Resilience

*It is critical that our buildings and infrastructure be built to withstand the tests which are increasingly being presented by more frequent natural disasters and other climactic concerns. The CSHub is working to quantify the resilience of our built environment and propose ways to keep ourselves and our assets safe.*

## Building to stand the test of time (and the climate)

### *Designing with longevity in mind*

MIT News’ most-read piece of all time, “Riddle solved: Why was Roman concrete so durable?,” features Admir Masic’s research uncovering why ancient structures like the Pantheon have stood the test of time. Their concrete was made through a technique called hot mixing (mixing concrete at extreme temperatures) which caused the lime deposits inside to become brittle and serve as a calcium source. When the concrete cracks, calcium carbonate forms to fill it, creating a material that is truly self-healing. Masic and his team have replicated the material and are working on making it scalable.

In materials science, it is critical to take lessons from the past to inform current practices. It is evident that, from the Roman example, structures can have exceptional longevity when designed with the future in mind. The future we face today will present us – as engineers, researchers, and stakeholders – with new challenges. Climate simulation models suggest that extreme climate events like flooding, hurricanes, and heat waves will become more frequent and more intense over time.

To protect our growing communities and economies from these threats, it is critical to construct the built environment to withstand them. The CSHub is investigating how to achieve this by investing in more resilient construction.

### *New methods to assess structural resilience*

To inform these investments, the CSHub is developing new metrics to understand structural resilience. In the April 2023 research brief “Kinetic temperature of structures: a new approach for building resilience assessment,” CSHub alum Konstantinos Keremidis describes a new method to assess the risk that a building design will be damaged by natural hazards like hurricane-force winds and fire. It assesses the kinetic energy acting on buildings during extreme climate events, examining when it causes structural and non-structural elements to fail. This represents an improvement over those fragility curves not offering a quantitative definition of these failures. The approach can help compare the performance of different building materials when exposed to hazards.

Under the direction of Franz-Josef Ulm, Research Assistants Ariel Attias and Athikom Wanichkul are investigating a physics-driven method to model how materials like concrete beams and slabs fracture when exposed to forces such as high wind loads. They have presented their work at events such as the 2023 ASCE Engineering Mechanics Institute Conference.

Among natural hazards, surface flooding is estimated to be the most serious climate-related risk to infrastructure for almost 40% of the world’s land area. Additionally, a majority of cities analyzed in a UN Department of Economic and Social Affairs report were found to be highly vulnerable to flood-related mortality and/or economic losses. It is evident that flooding poses a significant challenge to buildings and pavements, and it is critical to understand these risks.

One obstacle to quantifying these risks to date is the relatively high computational power required to run flooding simulations, as well as the difficulty in acquiring resources like maps of drainage networks. Research Assistant Danial Amini and

*Below: A large-area elemental map (Calcium: red, Silicon: blue, Aluminum: green) of a 2 cm fragment of ancient Roman concrete (right) collected from the archaeological site of Privernum, Italy (left). A calcium-rich lime clast (in red), which is responsible for the unique self-healing properties in this ancient material, is clearly visible in the lower region of the image.*

*Through the extended functional lifespan and the development of lighter-weight concrete forms, Masic hopes that these efforts could help reduce the environmental impact of concrete production. Along with other new formulations, such as concrete that can actually absorb carbon dioxide from the air, another current research focus of the Masic Lab, these improvements could help to reduce concrete's global climate impact.*

*— MIT News: "Riddle solved: Why was Roman concrete so durable?"*

CSHub alum Johannes Kalliauer explain their new, computationally-inexpensive method of modeling flooding in their November 2023 research brief, "Accessible Multi-scale Flood Modeling via the 3D Lattice Approach." Using a novel approach that accounts for city texture (how elements of a city are arranged with respect to one another), Amini and Kalliauer demonstrated how flooding could be modelled for the city of Cambridge, Massachusetts on a conventional desktop computer with widely available resources like OpenSteetMap on multiple scales. This tool could aid policymakers from all levels of government in designing flood mitigation strategies at little to no cost.

Simultaneously, Research Assistant Katerina Boukin continued her work on flood modeling methodologies that can better capture the dynamic, time-sensitive nature of flooding as well as city texture with the advisement of Kenneth Strzepek. She presented at meetings such as the American Geophysical Union's 2024 conference and was accepted to give an oral presentation at the ASCE Environmental & Water Resources Institute's Operation & Maintenance of Stormwater Systems Conference in April 2024.

In a similar vein, Research Assistant and now postdoctoral associate Ipek Bensu Manav earned her PhD in November for her work on integrating resilience-related risks into life cycle assessment methodologies. Her defense, "Assessing the Intersectional Risks Associated with the Full Life Cycle of the U.S. Housing Stock," focused on the use and end-of-life stages of the building life cycle, examining how factors like the environmental costs of repair and replacement impact environmental footprints.

### *Resilient construction advocacy*

In addition to providing tools to quantify resilience, the CSHub continues to be a thought leader in advocating for stronger, cooler construction. Summer 2023 was the hottest on record, and it is critical for cities and municipalities to act now to prepare for future heat waves and a hotter climate in general. Randolph Kirchain was featured in a Globe and Mail story about how cool pavements (like concrete) can lower ambient temperatures, especially when greening (e.g., creating green roofs) is not feasible. In a similar piece in Ask MIT Climate, Kirchain and Hessam AzariJafari note that almost 40% of the land surface of the typical city is paved, offering a significant opportunity to lower ambient temperatures by employing cool pavements.

On the topic of heat risk, Postdoctoral Associate and Fulbright Scholar Samira Garshasbi, a recent addition to the CSHub, is developing an urban climate model that assesses how the arrangement of buildings, the albedo of surfaces, and the thermal mass of materials influences energy consumption and sensitivity to extreme heat.

# Workforce

*In the wake of the COVID-19 pandemic, the concrete industry is facing unique workforce challenges. The MIT CSHub is working to understand, improve, and mitigate them.*

## A new, critical direction for the CSHub (and industry)

### *Transforming the Role of the Concrete Delivery Professional*

The MIT CSHub recently began exploring a topic outside of our usual focus on materials science, civil engineering, and econometrics: Key workforce issues that impact the concrete industry. We have undertaken a special project funded by the Concrete Advancement Foundation focused on understanding the shortage of concrete delivery professionals (CDPs) as well as recruitment and retention. According to the National Ready Mixed Concrete Association, 70% of concrete producers had to turn away business because their CDP workforce was insufficient to meet demand in 2021.

In our newly released report, "Transforming the Role of the Concrete Delivery Professional: A Study on Innovative Solutions for the Ready Mixed Concrete Industry," we detail our findings on immediate and long-term ways to address the CDP shortage and transform the role of the CDP. Our approach was informed by 25 stakeholder interviews, a job satisfaction survey of over 500 drivers, data from 36,000+ deliveries, and a simulation model of ready mixed concrete operations. This research was led by a team including Randolph Kirchain, Frank Field, Beth Unger, and Elizabeth Moore. Active engagement with industry and academic leaders has been critical to the success of this project. In April 2023, we welcomed over 40 of these professionals to MIT for a workshop focused on identifying innovative solutions for CDP recruitment and retention as well as the future of the profession.

Our research has identified a range of solutions that show promise in bolstering CDP recruitment and retention. Some of these include investment in technologies to make the job less demanding, like automated chutes. Adopting virtual and augmented reality devices for training and on-the-job assistance can help CDPs handle a wide range of scenarios; CDPs can learn what to do in the case of accidents and receive guidance with maintenance and troubleshooting. Similarly, standardizing CDP training can enable better access to foreign workers by, for instance, demonstrating technical qualifications which can be discussed in a visa application. Actions to improve scheduling consistency and managerial relations can improve the satisfaction of current CDPs while changing the perception of the job and targeting new candidate tools can help to attract new CDPs. Encouraging technology for bid-for-schedule and surge pricing would similarly allow CDPs to have more control over their schedules.

While the aforementioned strategies have been discussed in the context of increasing CDP recruitment, retention, and productivity, there are also sustainability implications. The analysis of 36,000+ deliveries highlights opportunities to reduce idle time and determine more efficient driving routes which can reduce greenhouse gas emissions and air pollution. The use of technology can also decrease resource use such as reducing the amount of concrete wasted as well as the electricity, fuel, and water used. For example, adopting automated truck washers can reduce the overall washing time and can also reduce the water footprint of the process. Many of the strategies to increase CDP productivity through data analysis and technology integration can also help lower environmental impacts during the transport, pouring, placement, and cleaning processes.

Improving recruitment and retention is critical to keep the concrete and construction industries moving, and the CSHub will continue investigating workforce issues in the CDP space.

*The concrete delivery professional (CDP) shortage shows no signs of abating. The American Trucking Association forecasts that the overall driver shortage could surpass 160,000 by 2030. The lack of truck drivers is projected to persist for the next ten years. Hence, it is vital that the ready mixed concrete industry* ***embraces transformative technology and operational models*** *to alleviate this pressure and increase individual CDP productivity.*

*— MIT CSHub Report: "Transforming the Role of the Concrete Delivery Professional: A Study on Innovative Solutions for the Ready Mixed Concrete Industry"*