Building Sustainability into Construction: Lifecycle, Resilience and Carbon Footprint

Jeremy Gregory/ MIT Concrete Sustainability Hub, USA, discusses ways in which concrete can become part of the solution for sustainable development.

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Building sustainability into construction requires an outlook far broader than most planners and builders currently take. From single-family residences to commercial complexes to roadways, the initial cost of construction continues to be a primary driver of decision making. Shortsighted and/or competing regulations and standards, as well as entrenched processes and methods, can also obstruct the long-term view of buildings and infrastructure – particularly the environmental impact and costs associated with the structures' decades of use.

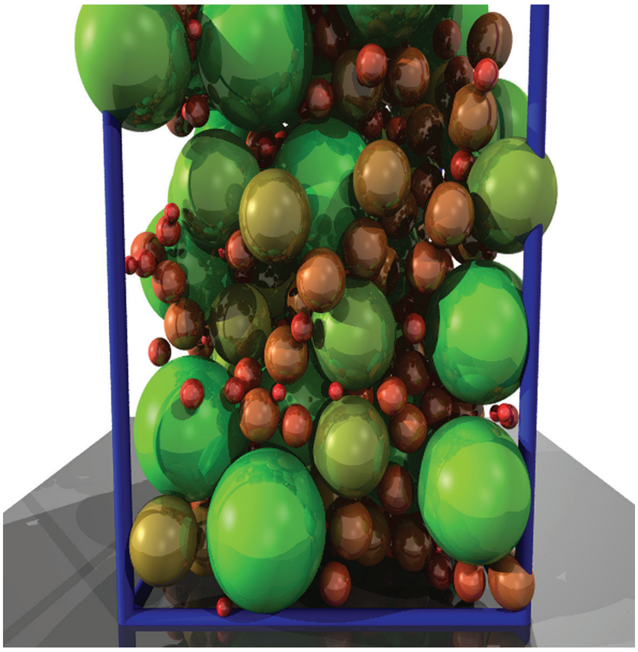
Nevertheless, the construction sector has begun a shift toward sustainability and so has its key material, concrete. The cement industry's carbon dioxide emissions have made it a target of those trying to mitigate climate change. At the same time, concrete is in greater demand than ever as, for example, developing nations become increasingly urban, extreme weather events necessitate more durable building materials and the price of other infrastructure materials continues to rise.

A sustainable society demands that this important building material be sustainable as well. This is the aim of the Concrete Sustainability Hub (CSHub), a research centre at the Massachusetts Institute of Technology that was launched in 2009 with support from the Portland Cement Association (PCA) and Ready Mixed Concrete (RMC) Research and Education Foundation. The centre's mission supports its attempt to advance lifecycle thinking in the construction industry. To achieve these goals a wide variety of research is conducted, encompassing everything from the basic molecular structure of cement to the economics of paving highways.

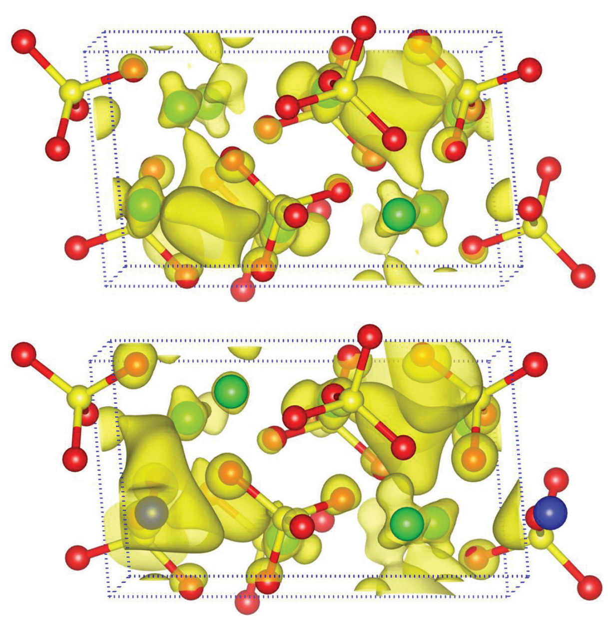
The CSHub investigates concrete at the nanoscale, examining ways to fine-tune its composition in order to improve resilience and reduce the greenhouse gas emissions produced during its manufacture. The centre also takes a systems view, quantifying the benefits that offset concrete's carbon footprint, such as minimising maintenance, repair and heating and cooling needs throughout the life of a structure.

The work carried out at the centre comprises a three-pronged strategy toward concrete sustainability: providing the scientific basis on which policymakers and the construction industry can make informed decisions about engineering projects; demonstrating the benefits of taking a lifecycle view that balances cost, environmental impact and performance; and transferring the results of the research into practice.

CSHub research shows that the size diversity of cement nanoparticles allows them to pack together tightly, increasing the strength of cement and, ultimately, concrete. (*Image courtesy of Enrico Masoero.*)



The image shows belite unit cells with silica represented by yellow balls, oxygen by red and calcium by green. The yellow blobs represent electron localisation. The top unit cell shows pure belite. The unit cell at the bottom shows belite that has been doped with magnesium (represented in blue) to increase its reactivity, which can be seen by the increased engagement of the electrons. (*Image courtesy of Can Ataca.*)



MIT is an ideal base for the CSHub, as it has a long tradition of working on practical problems affecting society and the economy and it is a leader in developing collaborative partnerships with industry. The CSHub works closely with the PCA and the RMC Research and Education Foundation to ensure that MIT's research is relevant to challenges faced by cement and concrete companies, as well as the designers and builders who use their products. All CSHub research is publicly available and subject to peer review through journals, conferences and other academic review panels.

MIT also excels at bringing many disciplines to bear on complex challenges. The CSHub's holistic approach to concrete sustainability involves preeminent researchers from the Department of Civil and Environmental Engineering, where the group is housed, as well as from the fields of materials science and engineering, engineering systems, chemical engineering and architecture.

Understanding the basics of concrete

Concrete sustainability begins at the most fundamental level: understanding the molecular structure of cement paste, calcium-silicate-hydrate (C-S-H), which forms and hardens when cement powder mixes with water (C-S-H inspired the name of the CSHub). The mechanisms that govern C-S-H's hardness and cement powder's reactivity to water occur at the nanoscale and have thus been challenging to study. CSHub researchers have created innovative computer models of C-S-H that shed new light on its molecular dynamics.

The models allow the centre to explore important features of concrete formation, such as how cracks begin to form in concrete at the atomic scale, the role water molecules play in shrinkage, creep and corrosion of hardened cement and how supplementary cementitious materials, such as flyash from electric coal power plants, affect the hydration phase of C-S-H. CSHub researchers have also applied rigidity theory, an analytical tool from glass science, to C-S-H with various ratios of calcium (derived from limestone) to silicate (derived from clay). This method enabled them to determine the optimal ratio that would make concrete structures impervious to cracks and other deformations.

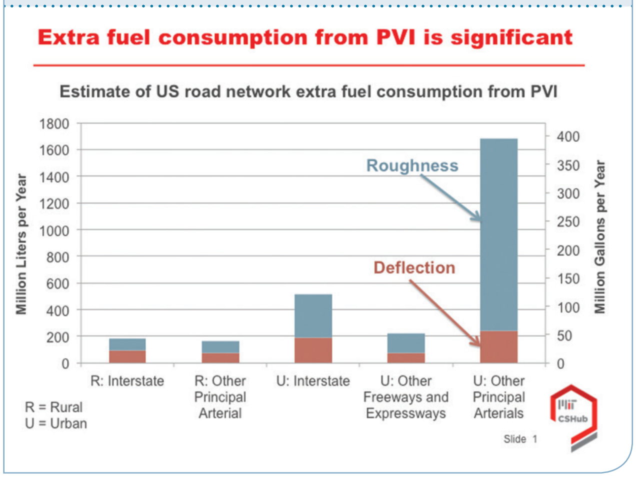
The goal of these studies is to discover methods to develop a more resilient concrete that lasts longer and requires fewer repairs over its use phase, as well as perhaps reduce the amount of cement powder needed to make concrete. Both would reduce the material's carbon footprint.

Another area of investigation focuses on the mechanisms of cement hydration through its main products, or silicate phases, alite and belite. Alite is highly reactive with water and thus speeds up the hardening of cement. Belite reacts more slowly and prolongs hardening time, but it gives cement strength while requiring less heat, and consequently less fuel, to sinter.

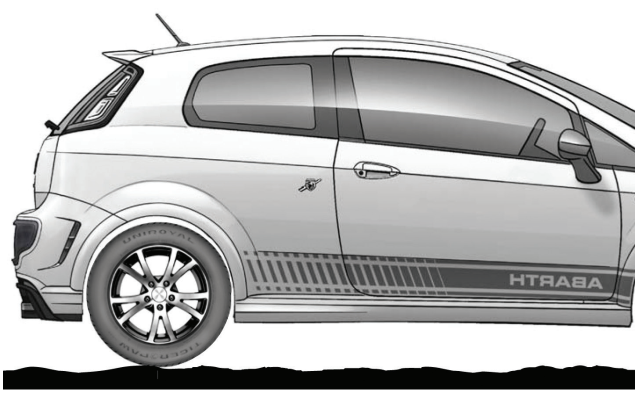
CSHub researchers have developed rigorous computer models of alite and belite crystals' reactivity to water, as well as examining how various impurities found in clinker (e.g. magnesium and aluminium) impact that reactivity. One project focuses on making belite more reactive by doping it with aluminium and sulfate during sintering. This would allow the industry to make a clinker that relies more heavily on belite than alite, thus lowering the sintering temperature and decreasing carbon dioxide emissions. Silicate phases also impact the energy required for grinding clinker into cement powder. More reactive alite and belite could enable coarser cements that require less grinding with no loss of early strength development or other performance characteristics.

The discoveries and validations that the CSHub's nanoscale models have made possible would have taken decades to achieve experimentally. Further refinement of these models and validation of their predictions (using alites and belites from commercial clinkers with realistic compositions) is underway.

Extra fuel consumption from PVI is significant. The chart depicts an estimate of fuel consumption from PVI on the US road network. (*Image courtesy of Mehdi Akbarian.*)



When the tyres of a car or truck roll over a roadway, the maximum pavement deflection is just behind the path of travel. This has the effect of making the vehicle's tyres roll continuously up a slight slope (exaggerated in this illustration), increasing the vehicle's fuel consumption. (*Image courtesy of Mehdi Akbarian.*)



Concrete's role in sustainable building

Along with pavements, buildings are one of the two primary application areas of CSHub research.

The construction sector makes up the largest fraction of greenhouse gas emissions in the US, representing 39% of nationwide CO_2 emissions. This environmental impact, along with the construction industry's major role in the economy, necessitate a better understanding of the lifecycle performance of residential and commercial buildings in order to reduce the sector's global warming potential.

The CSHub has undertaken a series of projects to quantify the full lifecycle carbon emissions of buildings, including the energy and resources required to construct, operate and dispose of buildings over time. Several lifecycle assessment (LCA) methods are currently in use, but their metrics can vary greatly and thus result in disparate predictions. Moreover, LCAs have traditionally been carried out in the commercial rather than the residential sector and they usually require a specialised consultant.

The centre aims not only to streamline but also to integrate uncertainty into LCA. The result would be a method that is accessible and useful to architects, clients and other decision makers earlier in the design process (where trade-offs can be better assessed) for both residential and commercial structures. The work includes a detailed analysis of both the operating or use phase of the lifecycle and the embodied phase associated with creating the materials and constructing the building. CSHub researchers are also developing better lifecycle cost analysis (LCCA) tools, enabling planners to more accurately estimate the financial outlay needed for long-term projects.

Part of this work, of course, involves analysing the trade-offs of using concrete as a building material. Concrete buildings can have comparatively higher emissions in the embodied phase, but lower emissions in the operating phase. To quantify such trade-offs, CSHub researchers have created a method to map thermal mass benefit in varied climates across the US. In the building trade, thermal mass strategies take advantage of the energy storage characteristics of high-mass materials, such as concrete, to moderate temperature. When integrated with a structure's orientation, window placement, shading and insulation, thermal mass strategies form the basis of a passive solar design that can reduce energy use.

In its effort to improve LCA and LCCA, the centre also emphasises the resilience of building materials by quantifying the hazard resistance of building structures. Extreme weather events such as Hurricane Sandy have changed the discourse on how to design buildings and assess risk. The benefits of durable materials such as concrete are increasingly part of those discussions.

Pavements and emissions: the full picture

As part of its research, the CSHub is taking a comprehensive look at the effects of different methods and materials used to pave roads. Unlike previous efforts to quantify pavements'

This house built from pre-cast concrete in Edmonton, Canada, is one of multiple case study homes that CSHub researchers will use as benchmarks in their research, which is focused on creating LCA tools that are more useful to decision-makers earlier in the design process. (*Image courtesy of Angela Robichaud.*)

lifecycle costs and emissions, this approach focuses on where the rubber meets the road, assessing the impact that different pavements have on vehicle performance. In addition, the models incorporate maintenance practices, including the emissions resulting from traffic delays and detours caused by road repairs, in their assessments.

Researchers have shown that the stiffness of a pavement has a small impact on vehicle gas mileage. Essentially, less-stiff roads that deform more as a vehicle passes over them create a small indentation beneath the wheels, so that to a very small extent the car is always going uphill and uses more fuel. Thereby, stiffer roads can provide a slight boost in efficiency that could reduce vehicle fuel consumption by as much as 3%. When this seemingly small number is multiplied by the total number of vehicles on the road, it could add up to a savings of 273 million barrels of crude oil per year in the US. This would result in an accompanying decrease in CO_2 emissions of 46.5 million tpa.

The computer models are more accurate than direct physical measurements at determining the impact of slight differences in pavement stiffness. To create the models, CSHub researchers analysed 12 specific types of roads, ranging from interstate highways to local surface streets, to account for the wide variations in usage patterns and climate conditions experienced by different roads. LCA studies that use the CSHub's model will be more comprehensive, providing a pathway for environmentally friendly road design and maintenance decisions.

Pavement roughness, which is much more commonly measured than stiffness, is also an area of study for the CSHub. The centre employs a method to use existing roughness and traffic data to estimate roughness-related fuel consumption in relation to pavement material and structure. A sample case study showed a significant impact on fuel consumption due to roughness – an increase of 30 000 gallons of fuel per mile over a 14-year test period.

Pavement research at the CSHub also evaluates the economics of road construction. Cost estimates for road projects frequently underestimate initial construction costs, as well as future spending, creating problems for budget-strapped agencies. Existing LCCA models typically employ the rate of inflation for the entire economy to estimate the cost of the materials that will be used for future road maintenance. This assumption can lead to inaccurate projections, as different paving materials can have different rates of inflation. The CSHub's price-projection models allow for the forecast of specific types of pavements by using historic data and considering uncertainty. Initial results show that these models are as accurate or better than the existing state-of-the-art technology. With a more accurate understanding of future materials prices, infrastructure officials can make strategic choices in light of limited budgets.

A sustainable future

The CSHub is delivering a new level of clarity for the industry, policymakers and designers and has created a foundation to build upon for future studies. The centre is conducting additional experiments on the composition of concrete to optimise its durability while minimising its carbon footprint. Reports on the lifecycle costs of buildings and pavements, in both cost and greenhouse gas emissions, are highly comprehensive and transparent. Furthermore, some of the most skilled researchers in concrete-related disciplines have been trained and are spreading their knowledge globally.

The ultimate goal is to implement the CSHub's findings into the engineering of infrastructure. By working with its industry partners and sharing results with building professionals and departments of transportation, the CSHub can bridge the valley between lab-scale inventions and full-scale innovation in engineering practice. As a result, concrete can become part of the solution for sustainable development that encompasses economic growth and social progress while minimising environmental impact.