A Multi-Discipline Approach to Quantifying and Enhancing Concrete Sustainability: The Concrete Sustainability Hub at Massachusetts Institute of Technology (MIT)

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Abstract

In late 2009, the Ready Mixed Concrete (RMC) Research & Education Foundation and Portland Cement Association established a Concrete Sustainability Hub (CSH) at the world renowned Massachusetts Institute of Technology (MIT). The MIT CSH is a multi-disciplined approach to quantifying and enhancing concrete sustainability through three major platforms – concrete science, building technology and econometrics. The concrete science platform is focused on first principles and understanding the genesis of concrete at the atomic level so that technology breakthroughs can then be scaled up into application by industry. The building technology platform is evaluating life cycle assessment (including critical operating phase) in combination with life cycle cost analysis for residential and commercial buildings and pavements. The econometrics platform is further evaluating the economics associated with potential policy changes and design decisions for a holistic view of how concrete contributes to sustainability and resiliency, and how it can be made even more sustainable into the future. The paper and presentation will include an overview of the MIT CSH program and the substantial findings from the first two and a half years of work.

Keywords

Sustainability, Massachusetts Institute of Technology, Life Cycle Assessment, Life Cycle Cost Analysis, Pavements, Buildings

Biographical notes

Julia Garbini is Executive Director of the RMC Research & Education Foundation. In this capacity, Mrs. Garbini manages the Foundation's various research and education projects, including representing the ready mixed concrete industry on the four-person Research Advisory Council for the Concrete Sustainability Hub (CSH) at Massachusetts Institute of Technology (MIT). The council sets the research agenda and monitors the progress of work at the MIT CSH.

In addition project management, Mrs. Garbini also leads the Foundation's fundraising activities, outreach and communications efforts, and financial management of the Foundation's endowment. Mrs. Garbini joined the Foundation as Executive Director in 2004 and has been affiliated with the concrete and construction industries since 1991.

1. INTRODUCTION

The MIT Concrete Sustainability Hub has been in existence for a short 2.5 years, yet is has already produced excellent progress toward advancing the sustainable nature of concrete and toward helping the design community, owners, government agencies and other stakeholders understand the opportunities in using concrete as a sustainable, long-lasting, and cost-effective building material.

2. The MIT CSH Platforms

The MIT CSH is a multi-disciplined approach to quantifying and enhancing concrete sustainability through three major platforms – concrete science, building technology and econometrics.

2.1 Concrete Science Platform

The Concrete Science Platform is driven by a “bottom up” approach that focuses on structure at the atomic to nano scale. The ultimate goal is to improve concrete engineering properties, with a particular emphasis on sustainability. The MIT CSH aims to revolutionize the scientific basis for evaluating the environmental impact of portland cement concrete, for optimizing the use of present materials, and for modifying present materials and developing new materials designed to achieve a fully sustainable physical infrastructure, including uses in ever more demanding environments.

The Concrete Science Platform has three major thrust areas: 1) dissolution, 2) precipitation, and 3) hardended paste. Some highlights of the progress so far include:

Alite/Belite Reactivity: The relative reactivity of different crystal faces for both C3S and C2S have been modeled. The model calculates theoretical energy for removing an atom from a crystal face, which is broadly related to dissolution energy (and grinding efficiency). Regarding impurities, model predictions for the relative reactivity of substitutions of many elements into a theoretical C2S crystal have been completed. This is a theoretical approach and whether such substitutions are thermodynamically possible or economically viable have been described as next steps. Repeating this work for C3S will be much simpler due to the experience generated in modeling C2S. For interactions with water, the first few nanoseconds of dissolution of one crystal face of alite or belite has been modeled.

Precipitation and Setting: For precipitation of products, the challenge is that chemical and mechanical changes occur over a wide range of time and length scales. In this work, atoms are arranged in interacting grains, which in turn are formed into agglomerations to represent the nanostructure of a cement paste. The modeling which has been completed allows those agglomerations to be tested virtually for physical properties, such as stiffness, strength, and toughness. Different size grains, distributions of sizes, and agglomerations are tested. These can be compared to physical test results on real pastes, such as nanoindenting or nanoscratching.

Hardened Paste: For the distribution of phases and microtexture, the thermo-mechanical properties of C-S-H (and C-A-S-H) are being evaluated in an attempt to improved sustainability of concrete by improving mechanical properties, such as strength and thermal conductivity. Nanoengineering may lead to improvements in thermal insulating properties of C-S-H, and therefore concrete walls in buildings. Stronger concrete sections could lead to more useable floor space in concrete buildings and fewer support structures in bridges, thus leading to reductions in the environmental impact of concrete construction. Modeling trends indicate that mechanical and thermal properties follow different trends with regard to the impact of water and

C/S ratio; therefore an optimum for a given application might be able to be created. Progress also has made on evaluation of C-S-H mechanical properties with respect to water content.

Although they represent different approaches, researchers at MIT CSH have been sharing information and collaborating as appropriate with the researchers of Nanocem. The MIT CSH researchers are also working very closely researchers at the U.S. Commerce Department's National Institute of Standards and Technology (NIST). Since 2000, NIST has been working on a Virtual Cement & Concrete Testing Laboratory (VCCTL) project at the microscale. The MIT CSH's work at the atomic to nanoscale, and now as it moves to the mesoscale in the next phase of work, directly feeds into NIST's work at the microscale. This collaboration will expedite the ability to bring MIT CSH's breakthroughs into application by industry.

The MIT CSH Concrete Science Platform publishes monthly briefs on their advancements. The briefs can be accessed at http://web.mit.edu/cshub/publications/researchbriefs_CSP.html.

2.2 Building Technology and Econometrics Platforms

Life Cycle Assessment/Life-Cycle Cost Analysis

Phase I findings of the LCA research was presented to an audience of more than 500 stakeholders in August, 2011. At this event MIT released three reports: *Methods, Impacts, and Opportunities in the Concrete Building Life Cycle*; *Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*; and the *Effects of Inflation and Its Volatility on the Choice of Construction Alternatives*. The LCA studies thoroughly examined the environmental impacts for the *full* life of pavements and buildings – including the critically important use or operations phase. Some key findings included:

- Compared to wood, single-family and multi-family concrete homes produce lower greenhouse gas emissions over a 60-year lifetime
- Single-family concrete homes consumed 8% less energy in Chicago (cold climate), and 11% less in Phoenix (hot, dry climate)
- In commercial structures, concrete frame consumed 3% less energy than steel
- For pavements, the study concluded that a proper and robust LCA analysis *must include* the use and rehabilitation phases. These areas account for 33-44% of the CO2 emissions in highways.
- Typical LCCA models that use a similar discount rate for both asphalt and concrete pavements will underestimate the cost of the asphalt road by 95% over a 50-year lifetime.

Copies of the Phase I reports, along with monthly briefs published by the Building Technology Platform, can be accessed at http://web.mit.edu/cshub/publications/researchbriefs_LCA.html.

A past challenge in understanding and calculating the impacts of the pavement use phase is the number of variables involved when measuring the fuel effiency of vehicles. Past studies have instrumented vehicles and measured fuel consumption as a means to understand the impact of pavement type on fuel consumption. However, temperature sensitivities, types of vehicles, pavement design, age and maintenance all greatly influence the results based on this approach. To overcome this challenge, MIT CSH has developed the first-ever mechanistic pavement-vehicle interaction (PVI) model that relates fuel consumption to structural properties.

3. MIT CSH Pavement-Vehicle Interaction Model

The MIT CSH's latest model represents a major breakthrough in evaluating the full life cycle of pavements, including the important use phase, which as previously noted accounts for 33-44% of the CO2 emissions for highways. The model, released in a peer-reviewed report in April, 2012, is the first to use mathematical modeling rather than roadway experiments to look at the effect of deflection on vehicle fuel consumption from the scale of a roadway section up to the entire U.S. road network. As nations and local municipalities around the world are challenged with both economic pressures and the goal of reducing global warming potential (GWP), this information is extremely important for designers, policymakers and individual consumers / taxpayers.

To put the findings into context, the MIT CSH research shows that using stiffer pavements on U.S. paved roads could reduce vehicle fuel consumption by as much as 3 percent. At an even more conservative estimate of 1 percent, that would add up to 91 million barrels of crude oil per year of $5.2 billion at today's oil prices when applied to the 250 million vehicles that travel those roads annually. This would result in an accompanying annual decrease in CO2 emissions of 15.5 million metric tons, the equivalent of the CO2 stored in roughly 3,800 square miles of trees.

By modelling the physical forces at work when a rubber tire rolls over pavement, the study's authors, Professor Franz-Josef Ulm and doctoral student Mehdi Akbarian, conclude that because of the way energy is dissipated, the maximum deflection of the load is behind the path of travel. This has the effect of making the tires on the vehicle drive continuously up a slight slope, which increases fuel use.

Stiffer pavements — which can be achieved by improving the material properties or increasing the thickness of the asphalt layers, switching to a concrete layer, or by changing the thickness or makeup of the sublayers of the road — would decrease deflection, thereby reducing the amount of fuel used and the environmental footprint of the pavement. The new study defines the key parameters involved in analyzing the structural (thickness) and material (stiffness and type of subgrade) properties of pavements. The mathematical model is therefore based on the actual mechancial behavior of pavements under load. To obtain their results, the researchers fed the model data on 5,643 representative sections of the nation's roadways taken from U.S. Federal Highway Administration data sets. These data include information on the surface and subsurface materials of pavements and the soils beneath, as well as the number, type and weight of vehicles using the roads. The researchers also calcluated and incorporated the pavement contact area of the vehicles' tires.

Ulm and Akbarian estimate that the combined effects of road roughness and deflection are responsible for an average annual extra fuel consumption of 7,000 to 9,000 gallons per lane mile on high-volume roads (not including the most heavily traveled roads) in the 8.5 million lane miles making up the U.S. roadway network. They say that up to 80 percent of that extra fuel consumption could be reduced through improvements in the basic properties of the asphalt, concrete and other materials used to build the roads. The researchers aim to include environmental impacts, pavement performance and eventually, a cost model to optimize pavement design and obtain the lowest cost and lowest environmental impact with the best structural performance. Their research points to the fact that the initial cost outlay for better pavements would quickly pay for itself not just in fuel efficiency and decreased CO2 emissions, but also in maintenance cost savings.

The full report, *Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements*, is available at http://web.mit.edu/cshub/news/pdf/PVI_Report-2012.pdf. Briefs on this issue are also available at http://web.mit.edu/cshub/publications/researchbriefs_LCA.html - see January and April 2012 briefs.

Acknowledgements and Resources

More information on the MIT CSH researchers and their work is available at http://web.mit.edu/cshub/index.html.

More information on the Ready Mixed Concrete (RMC) Research & Education Foundation and its resources, including all MIT CSH resources, is available at www.rmc-foundation.org.

The National Ready Mixed Concrete Association and Portland Cement Association have each developed additional collateral materials and educational programs around the MIT CSH research findings. More information on these resources is available at www.nrmca.org/sustainability and http://www.think-harder.org/MITResearch.aspx.

A separate, but related effort in which RMC, NRMCA and PCA all participate, is the Concrete Joint Sustainability Initiative. Resources and information on this initiative are available at www.sustainableconcrete.org.

Information for this paper has been excerpted from the MIT CSH briefs, press releases, and materials produced by the Portland Cement Association with permission and appreciation.