EXPLORATORY ADVANCED RESEARCH

EVALUATING AND IMPLEMENTING CC-I-L CEMENT FOR THE NEXT GENERATION OF CONCRETE BRIDGE CONSTRUCTION

April 2024

FACT SHEET

Sustainability has become a focus of cement production. Cement is second to water as humanity's most used substance. According to U.S. Environmental Protection Agency data, the manufacture of cement accounts for 1.25 percent of U.S. carbon emissions.(1) As a result, the desire for low-carbon cement has increased. The Federal Highway Administration's (FHWA) Sustainable Pavements Program has promoted research, publications, and strategies to support more environmentally friendly cement, including its 2016 TechBrief *Strategies for Improving Sustainability of Concrete Pavements*.(2,3)

In line with these goals, FHWA's Exploratory Advanced Research (EAR) Program is sponsoring a collaborative research team, consisting of individuals from Iowa State University, University of Florida, University of Texas-Austin, Georgia Institute of Technology, and Carnegie Mellon University, in a project to develop viable low-carbon calcined clay (CC)-based cementitious materials options for pavement and bridges called CC-I-L.

BACKGROUND

CC-based cement has emerged as a promising low-carbon alternative to ordinary portland cement (OPC). Many studies have shown that CC-based concrete displays excellent resistance to chloride penetration, mitigation of alkali-silica reaction (i.e., a chemical reaction that could damage concrete over time) with reactive aggregates, and sulfate resistance.(4,5,6) Research has also shown that the heat released during the first 72 h of CC-based cement hydration is generally lower than that of OPC, which would be beneficial for mass concrete bridge foundations.(7) Production of CC-based cement is associated with 40 percent less carbon emissions than OPC, and CC is also widely available, making it cost effective.(8)

One particular CC-based cement, limestone CC cement (LC^3), has attracted increasing attention. Research and pilot projects in India and Cuba have earned LC^3 the title of "game changer" for decarbonizing concrete.(8) Research in India and Switzerland has found the material to exhibit strong durability and longevity characteristics, but LC^3's use has been limited to houses (walls and tiles) and pavements. LC^3 has not been used for bridges.

The research team in this study plans to examine LC^3 along with two other categories of CC-I-L cement: CC and portland-limestone cement (CC-IL) and portland pozzolan cement with limestone powder (IP-L). This study's researchers want to accomplish the following:

- Provide various viable options for implementing sustainable cement.
- Identify gaps and develop strategies to overcome major barriers that prevent the implementation of CC-I-L cement.
- Advance the current knowledge and develop a roadmap for national and State-by-State implementation of CC-I-L cement in pavement and bridge construction.

STUDY OVERVIEW

The study is broken down into six major tasks:

- Characterize raw materials, optimize compositions, and streamline the CC-I-L testing process.
- Identify gaps, develop cement composition design tools, and optimize CC-I-L blends using machine-learning (ML) techniques.
- Evaluate the performance of CC-I-L cement mixes and link the research to practice.
- Develop models to predict CC-I-L cement hydration, adiabatic temperature rise (ATR), and thermal cracking via a ConcreteWorks software modification.(9)

U.S. Department of Transportation
Federal Highway Administration

FACT SHEET

- Conduct a field investigation to demonstrate the advantages and performance of CC-I-L cement in slab applications.
- Develop a roadmap for implementing CC-I-L cement in pavement and bridge construction.

Characterize Raw Materials, Optimize Compositions, and Streamline the CC-I-L Testing Process

In this task, the research team plans to develop an easily replicable process for creating CC-I-L cement. The team is evaluating three possible mixtures, CC-IL, IP-L, and LC^3 cement, and plans to develop the optimal CC-I-L cement blends for the three categories. This process begins with procuring the materials. In particular, the research team wants to develop CC-I-L using CC from different geographic regions to present flexible options for concrete producers that may have regional material supply constraints. The researchers will then characterize the materials and assess their reactivity. The cement components will be blended, maximizing clinker replacement (i.e., materials used in cement production that reduce carbon emissions) and optimizing gypsum (i.e., mineral added during cement production that influences the cement's strength and durability).

Identify Gaps, Develop Cement Composition Design Tools, and Optimize CC-I-L Blends Using ML Techniques

For this task, the researchers will analyze CC-I-L mixtures to determine the relationship between material composition, reactivity, and performance as well as how to reduce embodied carbon. To accomplish this goal, the researchers will use an ML technique known as transfer learning, where knowledge gained from solving one problem can be used to solve another. The ML models will receive input from a variety of data sources, such as research literature, industry partners, and government agencies. The researchers will develop ML models that predict hydration, setting, and strength development in CC-I-L cements and the suitability of a CC source. Then an ML model will be developed to determine the optimal sulfation level (i.e., the amount of sulfate ions present in cementitious material, which can harm the durability and performance of concrete structures) of CC-I-L cements.

Evaluate the Performance of CC-I-L Cement Mixes and Link the Research to Practice

The team will examine existing challenges to the use of CC-based concrete mixtures:

- Higher level of admixtures mixed in during concrete production to reduce the amount of water needed to achieve concrete slump (i.e., consistency).
- Possibility of increased autogenous shrinkage (i.e., contraction of concrete volume that occurs during production).
- Limited studies on its freeze-thaw durability.

The proposed project will include six tasks (T1–T6). Figure 1 summarizes the main activities in and the interactions between these tasks and potential benefits.

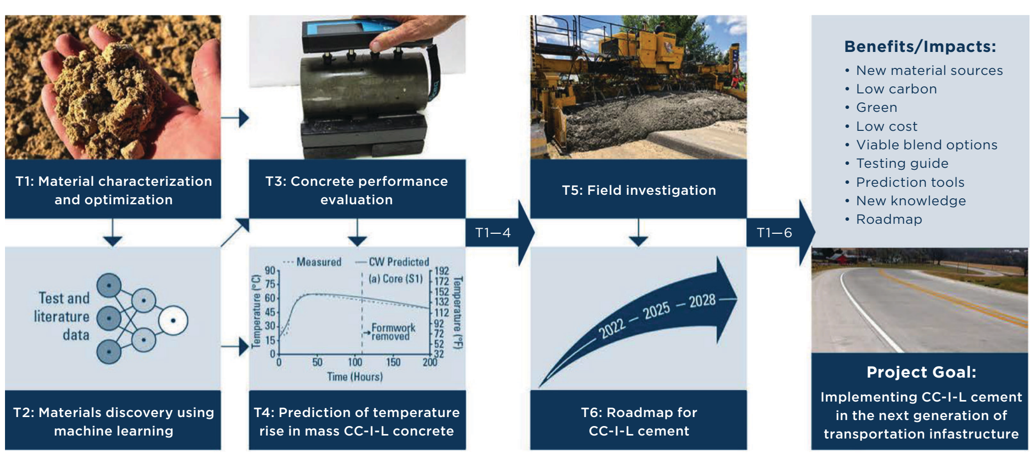

Figure 1. Overview of project tasks, benefits, and overall goal.

Seven concrete mixtures will be prepared and undergo property and strength tests. One of these mixtures will incorporate a portland-limestone cement that contains 20-percent fly ash cement replacement as a control mix to compare the results with the other CC-based mixes. The three most promising mixes will be adjusted with admixtures and tested again with overall performance evaluations in comparison to the control mix. See table 1 and table 2 for more details.

Develop Models to Predict CC-I-L Cement Hydration, ATR, and Thermal Cracking

This task aims to develop the relationships needed between CC-I-L cement compositions and heat of hydration development to facilitate the cement's use in construction scenarios. Using previous material blends from this study, the research team will examine CC-I-L cement's temperature sensitivity and ATR (i.e., the increase in temperature in a concrete mixture during production due to chemical reactions) and use data analytics to determine the relationship between composition and performance. The research team will use isothermal calorimetry (i.e., measuring the heat released from the cement when it is combined with water) performed at 10 °C, 23 °C, 40 °C, 60 °C, and 80 °C to calculate the CC-I-L cements' temperature sensitivity as an apparent activation energy. The isothermal calorimetry results will also be used to calculate a concrete ATR. The team will then use data analytics to quantify the relationship between CC-I-L composition, reactivity, and concrete mixture proportions with ATR. Such information will allow CC-I-L cement to be evaluated for construction purposes using simulation software.

Conduct a Field Investigation to Demonstrate the Advantages and Performance of CC-I-L Cement in Slab Applications

The team will create a test slab using CC-I-L cement to demonstrate its viability. The slab will be evaluated for its constructability, initial acceptance criteria, potential durability, and its economic and environmental impact. The construction process will be monitored, and during that time, quality control tests will be conducted and embedded sensors will track strength gain, warping, and drying. The team will extract samples, or in situ tests will be run to evaluate permeability, maturity, abrasion resistance, and cracking. Freeze-thaw durability will be tested using field samples and by monitoring the slab over time. For the environmental and economic cost analysis, environmental impacts and lifecycle costs will be calculated based on the field data.

Mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
	IL-20FA	CC-IL-X1	CC-IL-X2	IP-L-X1	IP-L-X2	LC^3-X1	LC^3-X2
Tests	Fresh Concrete Properties Tests				Strength Tests		
	Set time	Slump		Air content	Compression	Splitting tensile	Flexural

20FA = 20-percent fly ash.

Table 1. Basic concrete mixtures for fresh property and strength evaluation.

Mix	Mix 1	Mix 8	Mix 9	Mix 10
	(IL-20FA)	(CC-IL-optimal)	(IP-L-optimal)	(LC^3-optimal)
Fresh Property Tests	**Mechanical Property Tests**			**Durability Tests**
Set time, slump, air content	Compressive/splitting/flexural strength and elastic modulus			Autogenous/free drying/ring shrinkage, surface resistivity, freeze-thaw

Note: Mixes 8–10 are selected from mixes 2–8 with adjustment in water ration and air-entraining admixture dosages to reach approximately 4 inches slump and approximately 6 percent air, respectively. Another set of samples from mix 8 will also be cured under an accelerated curing condition (approximately 140 °F).

Table 2. Optimized concrete mixes to be used for overall performance evaluation.

FACT SHEET

Develop a Roadmap for Implementing CC-I-L Cement in Pavement and Bridge Construction

Drawing on its research, the team will develop technical papers, tech briefs, presentations, and webinars that will sketch a roadmap for adopting CC-I-L cement in pavement and bridge construction. This roadmap will provide background, research, and changes in practices needed to use the new CC-I-L material. The researchers will also engage various infrastructure owner-operators to consider trials and test sections using the CC-I-L cement. The team will then work with the American Association of State Highway and Transportation Officials and ASTM International to adapt existing or adopt new language that will permit the use of such materials in public structures.

REFERENCES

[1]Portland Cement Association. 2021. “Roadmap to Carbon Neutrality” (web page). https://www.cement.org/sustainability/roadmap-to-carbon-neutrality, last accessed February 16, 2024.

[2]FHWA. 2023. “Sustainable Pavements Program” (web page). https://www.fhwa.dot.gov/pavement/sustainability/, last accessed January 24, 2024.

[3]Snyder, M. B., T. Van Dam, J. Roesler, and J. Harvey. 2016. *Strategies for Improving Sustainability of Concrete Pavements*. Publication No. FHWA-HIF-16-013. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/pavement/sustainability/hif16013.pdf, last accessed January 24, 2024.

[4]Scrivener, K., F. Avet, H. Maraghechi, F. Zunino, J. Ston, W. Hanpongpun, and A. Favier. 2019. “Impacting Factors and Properties of Limestone Calcined Clay Cements (LC^3).” *Green Materials* 7, no. 1: 3–14, https://doi.org/10.1680/jgrma.18.00029, last accessed February 16, 2024.

[5]Sharma, M., S. Bishnoi, F. Martirena, and K. Scrivener. 2021. “Limestone Calcined Clay Cement and Concrete: A State-of-the-Art Review.” *Cement and Concrete Research* 149: 106564.

[6]Antoni M., J. Rossen, F. Martirena, and K. Scrivener. 2012. “Cement Substitution by a Combination of Metakaolin and Limestone.” *Cement and Concrete Research* 42: 1579–1589.

[7]Krishnan, S., A. C. Emmanuel, and S. Bishnoi. 2019. “Hydration and Phase Assemblage of Ternary Cements with Calcined Clay and Limestone.” *Construction and Building Materials* 222: 64–72, https://doi.org/10.1016/j.conbuildmat.2019.06.123, last accessed February 16, 2024.

[8]Raju, S. S., and R. Lalit. 2023. “Unleashing the Potential of Limestone Calcined Clay Cement (LC3).” *Rocky Mountain Institute*, August 10, 2023. https://rmi.org/unleashing-the-potential-of-limestone-calcined-clay-cement/, last accessed January 24, 2024.

[9]Concrete Durability Center. 2007. *ConcreteWorks* (software). Version 3.1.1.2.

Non-Binding Contents

Except for the statutes and regulations cited, the contents of this document do not have the force and effect of law and are not meant to bind the States or the public in any way. This document is intended only to provide information regarding existing requirements under the law or agency policies.

What Is the EAR Program?

The EAR Program supports longer term, higher risk research with the potential for transformative improvements to the U.S. transportation system. The EAR Program seeks to leverage promising expertise and advances in science and engineering to create breakthrough solutions to highway transportation issues.

To learn more about the EAR Program, visit https://highways.dot.gov/research/exploratory-advanced-research.

LEARN MORE

For more information about this EAR Program project, please contact Michelle Cooper (202-493-3691 or michelle.cooper@dot.gov), laboratory manager of the FHWA Concrete Laboratory.

Recommended citation:
Federal Highway Administration, *Evaluating and Implementing CC-I-L Cement for the Next Generation of Concrete Bridge Construction* (Washington, DC: 2024)
https://doi.org/10.21949/1521491

FHWA-HRT-24-057
HRTM-30/04-24(WEB)E

U.S. Department of Transportation
Federal Highway Administration