The Exploratory Advanced Research Program Fact Sheet

Supplementary Cementitious Material Advancements

Helping to Make Longer Lasting Concrete Highways and Transportation Structures

Exploratory Advanced Research . . . Next Generation Transportation Solutions

Fly ash, a supplementary cementitious material (SCM), is an important constituent in the production of concrete. Although demand for SCMs is increasing, the amount of fly ash produced by coal-fired power plants is decreasing, and so the transportation industry is looking for viable alternatives to traditional fly ash that can provide reliable performance. These alternatives, which include nontraditional or off-specification fly ash as well as other SCM sources, are promising because of their abundance and potential economic value. Three projects supported through the Federal Highway Administration's (FHWA) Exploratory Advanced Research (EAR) Program seek to study and document how the chemical and physical properties of these alternative materials affect the performance of concrete. These projects aim to provide State Departments of Transportation with information that describes how these materials affect the durability, sustainability, and strength of concrete so that engineers can make informed and timely decisions regarding materials specifications and concrete mixture performance criteria.

Why Study Ways to Improve Concrete

Concrete's presence is ubiquitous. Concrete—a mixture consisting of cement, water, and aggregates such as rock, gravel, and sand—is used to make bridges, sidewalks, and roads. Highway professionals use concrete for its economy and availability, and because it can be molded to conform to the needs of the pavement or structure. Its properties can also be designed to meet a wide variety of targeted strength and durability objectives.

However, concrete production faces several challenges. First, it can be costly to produce concrete using ordinary portland cement (OPC) as the sole binding agent because, as a finite natural resource, it is the most expensive component of the mixture. Use of OPC alone may also increase the risk of such concrete durability problems as alkali silica reactivity (ASR) and chemical degradation due to exposure to deicing chemicals. In addition, production of portland cement is a significant source of global CO_2 emissions (about 8 percent of the total CO_2 emissions caused by humans).[1]

One way to address these challenges is to reduce the net amount of cement (that is, reduce the OPC content) that's used to make concrete, and instead use other, often alumina- and silica-rich substances that complement OPC's chemical characteristics. Engineers call these other substances SCMs.

The Limited Availability of Fly Ash

Fly ash, a by-product from coal-fired power plant combustion, is an economical and effective SCM, but fly ash itself has its own challenges. The supply of fly ash is shrinking, even as the demand for it and other SCMs is growing. Scientists estimate that U.S. demand for fly ash will exceed 35 million tons per year in 2030, while the availability of SCMs, including fly ash, is projected at 14 million tons per year.[2]

To address this looming shortage, researchers have been looking at alternative fly ash sources and other alternative SCMs. While the EAR Program-supported research projects use different approaches in their research of SCMs, they all share the mutual goal of developing an understanding of how and when to apply SCMs for specific performance requirements. Their research can provide a foundation of knowledge that State Departments of Transportation and other relevant stakeholders can lean on as they consider and utilize these alternative SCM sources and consider the necessary specifications and test method changes that will facilitate the use these materials.

U.S. Department of Transportation
Federal Highway Administration

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Studying the Viability of Nontraditional SCMs

While fly ash is a dominant choice among SCMs, there are other types of materials that could also be used for concrete production. These other types of materials include nontraditional and natural pozzolans such as volcanic ashes, low-purity calcined clays, ground bottom ashes, and fluidized bed combustion ashes. Researchers at Purdue University, with assistance from researchers at Penn State University and Clarkson University, are seeking to analyze and conduct further studies on how these types of SCMs might perform in concrete pavements or other transportation structures in their project "Nontraditional and Natural Pozzolan-Based SCMs or Inorganic Polymers for Transportation Infrastructure."

A clipboard showing samples of fly ash before and after electrostatic separation to reduce the amount of carbon in fly ash. The dark gray/black contains the carbon removed from the fly ash, the medium gray is the fly ash entering the separation system, and the light gray is the fly ash product to be used in concrete. *Source: FHWA.*

These nontraditional sources—calcinated clays, natural pozzolans, bottom ashes and fluidized bed combustion ashes—are cost-competitive and relatively abundant in different U.S. regions. Laboratory tests can create an understanding of how these resources could be utilized as viable alternatives to fly ash.

The researchers aim to reach several objectives. They want to characterize and quantify the chemical and physical properties of these SCMs and determine how these properties might maximize their performance in concrete. They also want to develop new test methods to evaluate the quality and performance of these SCMs.

The researchers also want to see how these SCMs can help slow the deterioration of concrete, making it more resistant to external factors such as freezing and thawing, moisture, and exposure to deicing chemicals, as well as to traffic and other environmental loading. ASR develops when a form of silica present in aggregates chemically reacts (in the presence of moisture) with the alkalis in the cement to produce a gel-like substance. This gel-like substance imbibes moisture and grows in volume over time, causing the concrete to expand and crack. Fly ash typically helps to minimize or eliminate this type of deleterious reaction.

"That's one of the impetuses behind this research: to look into other avenues for finding supplementary cementitious materials that do the same thing as fly ash," said Ahmad Ardani, research materials engineer with the FHWA Office of Infrastructure Research and Development. "There is insufficient scientific knowledge related to the reaction mechanisms and the rates of application, for example, in the short- and long-term performance of these nontraditional resources.

Using Artificial Intelligence to Find Viable Fly Ash Alternatives

Researchers at the University of California, Los Angeles (UCLA) are seeking to develop what they're calling "new data-guided pathways" to help determine which grades of fly ashes, including reclaimed and off-spec fly ashes, can be used in the production of concrete for highway construction applications. The project, "Physically Informed Data-Driven Methods for Greatly Enhancing the Use of Heterogeneous Cementitious Materials in Transportation Infrastructure," aims to decipher, through a data-guided and machine learning approach, how the physical and chemical features of fly ashes—the "genome" of the fly ash—control their performance in concrete. Machine learning consists of using artificial intelligence tools and programs to sort through large amounts of data and seek trends or patterns within the data.

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The "genome" of the fly ash can be thought of "in the same fashion as human DNA governs the characteristics of each individual," said Gaurav N. Sant, principal investigator for the UCLA team. UCLA is working with the Missouri University of Science and Technology, Arizona State University, and Boral Materials on this project, in collaboration with standards-developing organizations.

Images represent two of the 11 pozzolanic materials. The material in the black container (top) is the natural pozzolan, and the material in the white container (bottom) is the fluidized bed combustion fly ash. *© Purdue University, Lyles School of Civil Engineering.*

So far, UCLA has developed a deep learning model that can accurately predict concrete's strength as different kinds of fly ash replace cement in the mixture. The model can help users assess how to maximize the fraction of fly ash in concrete while ensuring that the resulting concrete meets a given target strength, according to the researchers. They are now expanding this deep learning model to take into account the chemical composition of fly ash.

The researchers based their efforts on concepts laid out by the Materials Genome Initiative, which seeks to use advancements in artificial intelligence, machine learning, and simulations to better the way materials are discovered, investigated, and manufactured. They hope to use this tool to gauge the suitability of fly ash as a replacement for a portion of the cement in concrete production and thus reduce the uncertainty surrounding the performance and ability of alternate fly ashes to make concrete production less costly overall.

"We would like to use the insights provided by this project to explore the possibility of greatly expanding the suite of fly ashes that can be used to replace cement in concrete. This would facilitate the use of diverse fly ashes in concrete in a timely, unprecedented, and unparalleled manner without compromising on engineering performance," Saurav said.

Assessing the Performance of "Reclaimed" Fly Ashes

Much of the fly ash used in concrete production is of a certain specification grade. But there are landfills and impoundments of other, older fly ash that have been stored over the last 50 to 60 years. It's that fly ash—what Oklahoma State University researchers call "reclaimed" fly ash—that researchers want to study to see if they provide viable alternatives to the approved fly ash sources currently in use.

"There's some concern about how these fly ashes have changed in storage. Are they useful? Do they have other problems? And so, our work is trying to develop a couple of different ways to evaluate the fly ash and see if it's good to use," said principal investigator Tyler Ley with Oklahoma State.

For the project "Performance-Based Classification Methods for Reclaimed Fly Ash," researchers at Oklahoma State, with help from the Georgia Institute of Technology, Ohio State University, and Diversified Engineering Services, seek to combine advanced material characterization methods, performance-based testing, mechanistic modeling, and machine learning to create engineering tools to classify reclaimed fly ash. Also involved in the project as collaborators are Boral Materials, the Minnesota Department of Transportation, the Oklahoma Department of Transportation, and Southern Company.

The project involves taking existing performance-based tests and tweaking them to better analyze the reclaimed fly ash and determine how it might perform when used for concrete production. The researchers want to capture the differences in chemical composition among the various reclaimed fly ashes and see how those differences can be measured in such a way that describes how

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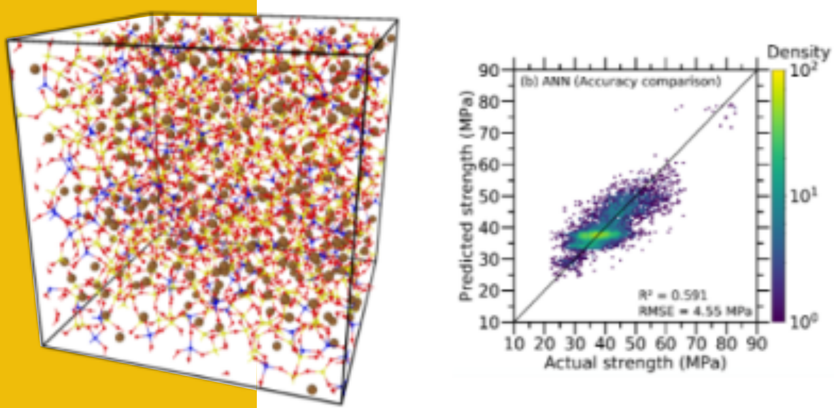
that fly ash performs in concrete. The team also expects to integrate machine learning into the process to combine all the test data together to see what patterns arise.

Ultimately, the researchers hope to provide State Departments of Transportation with a tool



(a) (b)

A comparison between the measured and predicted 28-day compressive strength in concretes comprising various fractions of fly ash. Predictions are obtained based on an artificial neural network, which mimics neurons in human brains. *© University of California Los Angeles.*

to determine how to choose which reclaimed fly ash to use for highway and transportation projects. They want the tool—a new performance-based classification method for fly ash—to act like an ingredient label that describes how varieties of reclaimed fly ash can make concrete stronger or longer lasting through differences in hardening, permeability, and resistance to ion penetration. They also want their research to inform and potentially update existing standards and testing methods related to fly ash that are widely used in the construction industry.

"We want to make sure that these new materials fit into what the States are doing now as closely as possible. If it doesn't, then we need to at least warn them about that," said Ley.

EXPLORATORY ADVANCED **RESEARCH**

What Is the Exploratory Advanced Research Program?

The EAR Program addresses the need for longer term, higher risk research with the potential for transformative improvements to transportation systems. The EAR Program seeks to leverage advances in science and engineering that could lead to breakthroughs for critical, current, and emerging issues in highway transportation by experts from different disciplines who have the talent and interest in researching solutions and might not do so without EAR Program funding.

To learn more about the EAR Program, visit https://highways.dot.gov/research/exploratory-advanced-research. The website features information on research solicitations, updates on ongoing research, links to published materials, summaries of past EAR Program events, and details on upcoming events.

Learn More

For more information about the UCLA project, contact Jack Youtcheff at 202-493-3090 (email: jack.youtcheff@dot.gov). For the Oklahoma State University project, contact Richard Meininger at 202-493-3191 (email: richard.meininger@dot.gov). For the Purdue project, contact Ahmad Ardani at 202-493-3422 (email: ahmad.ardani@dot.gov). All three FHWA contacts are affiliated with the FHWA Office of Infrastructure Research and Development located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA.

Photo credit, page 1: A mixer truck gets into position to receive cement. *Source: FHWA.*

[1] Andrew, R. M. (2018). "Global CO2 emissions from cement production." Earth Syst. Sci. Data. 10:195–217. Available online: https://doi.org/10.5194/essd-10-195-2018. Last accessed June 8, 2020.

[2] Production and Use of Coal Combustion Products in the U.S. - Market Forecast through 2033. (2015). American Road and Transportation Builders Association.

Publication No.
FHWA-HRT-20-048
HRTM-30/08-20(WEB)E