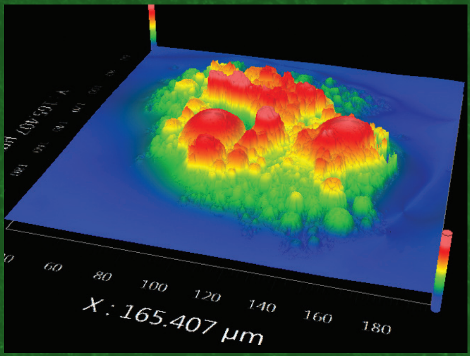
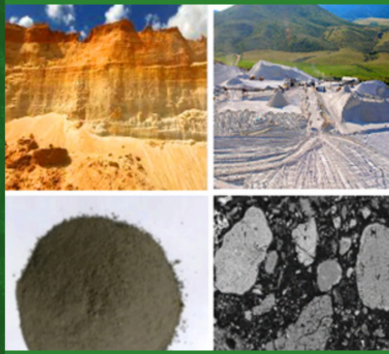
EXPLORATORY ADVANCED RESEARCH

Exploratory Advanced Research Program

Cultivating Materials Science Research to





Benefit Surface Transportation 2022 Update

U.S. Department of Transportation
Federal Highway Administration

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Contents

Introduction

Bridges and pavements must bear heavy cars and trucks over a sustained period and withstand weather conditions, such as rain and snow or extreme heat and cold, that can wear down materials over time. To combat the wear and tear that bridges and highways face, researchers are keen to explore how to build durable and longer lasting structures and pavements. One way to approach this problem is through materials science, a multidisciplinary field that studies the production and use of materials through the lenses of chemistry, physics, and engineering.

Breakthrough research in materials science is beneficial to surface transportation. Such work can produce improved materials used to build more durable yet still affordable highway bridges and pavements. Thus, by actively supporting materials science research, the Federal Highway Administration's (FHWA) Exploratory Advanced Research (EAR) Program is investing in the longevity and cost effectiveness of U.S. highway infrastructure.

One of the EAR Program's objectives is to support materials science research that results in the construction of more durable and longer-lasting bridges. © 2017 Patrick Zickler.

What Is Materials Science?

In materials science, researchers study the interaction of materials of different chemical properties (weight or mass, chemical composition, and structure). The observations gained from these interactions help researchers and companies develop improved products. For instance, in surface transportation, researchers have been looking at how to manipulate concrete production so that concrete is more durable and impervious to adverse conditions. Concrete, at its simplest, consists of ordinary portland cement and aggregate materials like sand, gravel, and water. Researchers are studying how altering the chemical composition of ingredients affects concrete production and concrete's characteristics.

FHWA supports innovation in materials science to provide a greater range of predictable materials for constructing and repairing bridges and pavements. For the EAR Program, FHWA support and funding have focused on developing highway materials that not only emphasize enhanced functionality but also stress sustainability and cost savings.

Research development in materials science can veer into many different directions. Some research developments investigate the inherent properties of the materials used in construction. Researchers are looking at the particles that make up the building materials and examining how changes in the chemical and mechanical makeup of these particles affect their size or their relationships with each other.

Other research developments include improving the predictability of using recycled materials, such as coal ash, as a supplement to make more environmentally friendly and cost-effective building materials and developing new coatings systems for steel surfaces to improve the ease of application on and long-term durability of steel surfaces.

Another development is the application of microscopic and nanoscale components that can be embedded in structural elements and pavements to help gauge their interior health. These nanoscale components may be able to sense changes in the chemical composition of the materials or help structural elements and pavements detect and adapt to the changes in the physical pressures being exerted upon them before damage is visible or irreversible.

In Search of Building Better Bridges

Many of the recent EAR Program-sponsored research initiatives fulfill a key FHWA goal of building better highway bridges, structures, and pavements. By combining techniques developed within chemistry and physics, these projects have focused on developing new materials that improve the durability, longevity, and resistance to adverse conditions (such as extreme temperatures and sustained load bearing) of infrastructure.

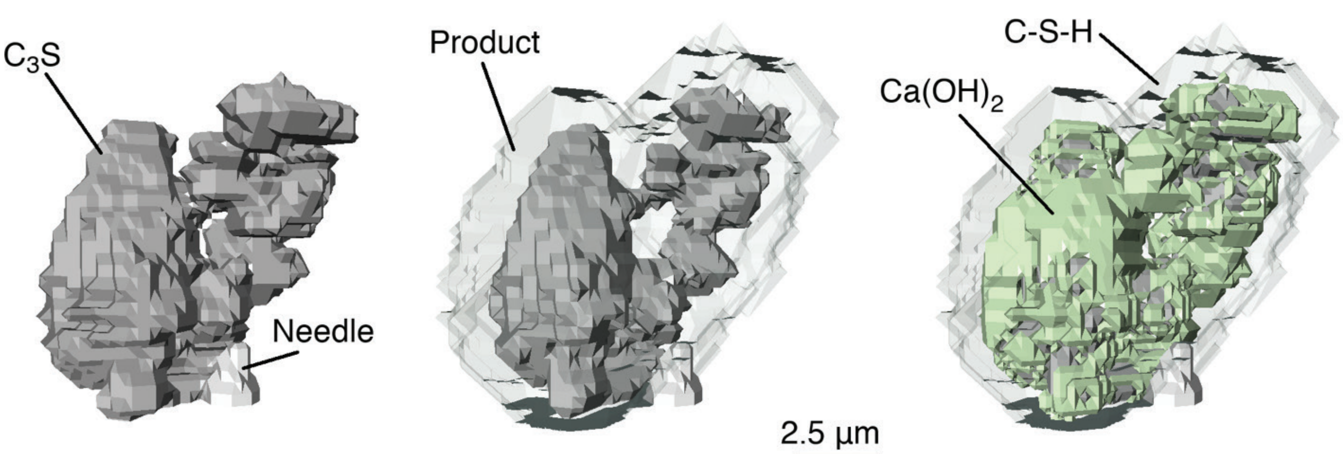
Research into Traditional Cement

One EAR Program research area has been to study concrete at the molecular level. This research includes examining the chemical properties of ordinary portland cement and the chemical reactions that occur within the substance over time so that researchers can better understand how ordinary portland cement behaves. It also includes studying the mechanical properties of concrete at the nanoscale level to better understand how concrete responds under different environmental conditions.

Researchers for the project "**Mechanisms of Hydration and Setting of Ordinary Portland Cement in Simple and Complex Systems**" studied how ordinary portland cement, an ingredient used to make concrete, behaves chemically and structurally.[1] The researchers from Princeton University, Oklahoma State University, University of California at Santa Barbara, Rice University, and W.R. Grace sought to understand the chemical reactions that occur during hydration or when concrete is in a slurry state. They also wanted to know how these chemical reactions affect the hardening, strength, and durability of concrete.

With support from the FHWA EAR Program and Office of Infrastructure Research and Development, researchers developed innovative analytical techniques that provided a more direct observation of reactions at the micro and nanoscales. These techniques further enabled researchers to develop hypotheses on the chemical reactions that occur during and after concrete's hydration stage, and they created computer models based on these hypotheses. These computer models will help guide engineers, practitioners, and stakeholders to produce more durable and cost-effective concrete.

The project "**Mechanical and Structural Nanoscale Modeling**" focused on refining multiscale modeling, particularly at the nanoscale level. Researchers at the Virginia Polytechnic Institute and State University developed a multiscale modeling theory that addressed the existing gaps in understanding multiscale modeling at



Researchers with the project "Mechanisms of Hydration and Setting of Ordinary Portland Cement in Simple and Complex Systems" developed a computer model that shows how particles respond and change as they undergo simulated hydration. The leftmost illustration shows the sample before hydration. The middle and rightmost illustrations show how the particles look after 7 h of simulated hydration. © The American Ceramic Society.

the nanoscale level. They created a digital specimen and digital test technique that used multiscale computerized tomography imaging to observe and analyze materials' behavior. They used this technique to develop a multiscale dynamic theory and an integrated thermochemical and electromagnetic theory, which then served as the basis for software that could enable researchers to bridge different scale and structure simulations.(2)

For the project "**Nano Material and Simulation by New Multiple Length/Time Scale Theories and Algorithms,**" researchers at the George Washington University developed theories and computational codes, such as algorithms, that would serve as a basis for understanding how materials behave over multiple lengths of time and at different scale sizes. These theories dealt with modeling and simulations at the nanoscale level. The goal of producing these theories was to provide a foundation for engineers and researchers to study how materials respond to environmental conditions and applied loadings over time.(3)

Research into Supplementary Materials

Another EAR Program research area focuses on how supplementary materials, or the materials other than ordinary portland cement that are used to produce concrete, can be developed to help make the end product more cost-effective and environmentally friendly without sacrificing durability.

For the project "**Nontraditional and Natural Pozzolan-Based Supplementary Cementitious Materials (SCMs) or Inorganic Polymers for Transportation Infrastructure,**" researchers from Purdue University, Penn State University, and Clarkson University seek to explore nontraditional and natural pozzolan SCMs as alternatives to fly ash, the predominant SCM in concrete production, which is increasingly in short supply. The researchers seek to characterize the chemical and physical properties of these SCMs and create new test methods for evaluating their quality and performance. They want to compare the performance of nontraditional and natural pozzolan SCMs to that of fly ash in mitigating the deterioration of concrete.(4)

Researchers at the University of California, Los Angeles (UCLA) are seeking 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 concrete production. Using a data-guided, machine-learning approach in their project "**Physically Informed Data-Driven Methods for Greatly Enhancing the Use of Heterogenous Cementitious Materials in Transportation Infrastructure,**" they want to understand how the physical and chemical features of different grades of fly ash control their performance in concrete. The UCLA researchers have already created a deep learning model that can accurately predict concrete's strength as various kinds of fly ash replace cement in the mixture. They hope that ultimately

Four classes of nontraditional and natural pozzolan studied in this project. © 2020 Farshad Rajabipour.
FBC = fluidized bed combustion.

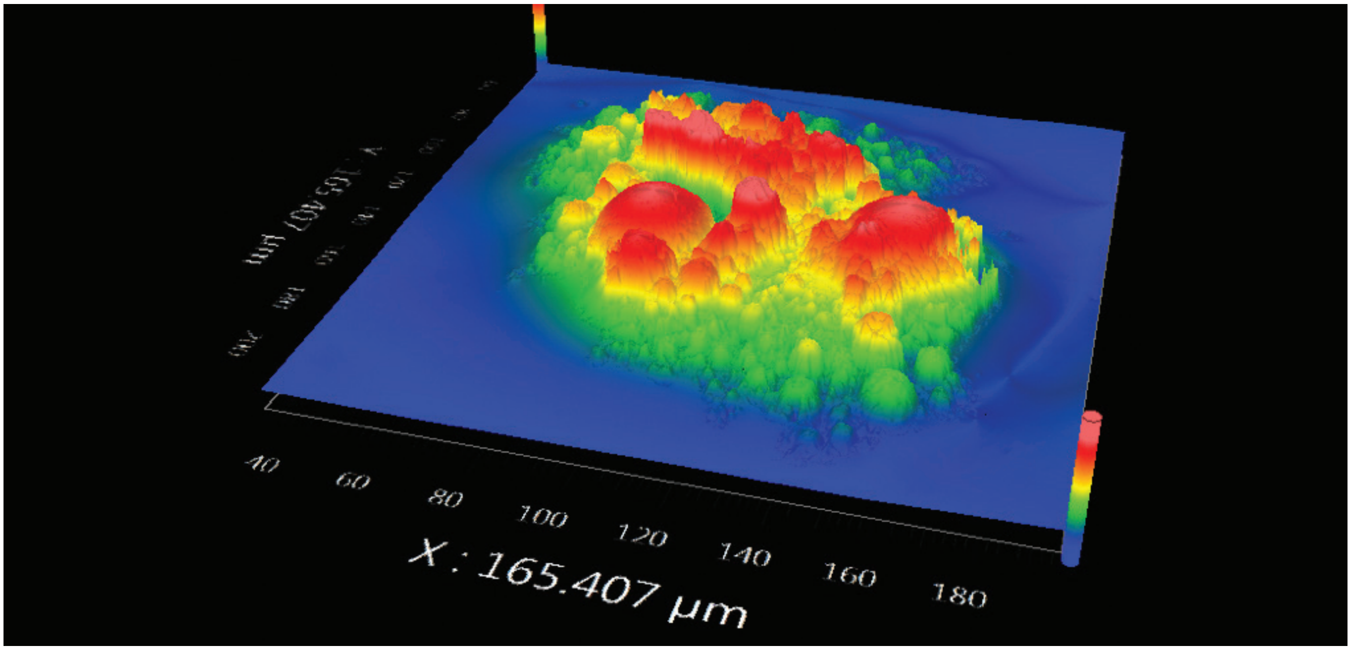
such use of machine learning can help expand the types of fly ash that can be used in concrete production without sacrificing engineering performance.[4]

Reclaimed fly ash is fly ash that has been stored in landfills and impoundments in the past 50 to 60 yr. For the project "**Performance-Based Classification Methods for Reclaimed Fly Ash,**" researchers from Oklahoma State University, 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. The researchers want to apply existing performance-based tests to analyze reclaimed fly ash and determine how it might perform when used for concrete production. The research team aims to provide State departments of transportation (DOT) with a tool to determine which reclaimed fly ash to use for highway and transportation projects.[4]

Researchers at UCLA, along with partners at the University of California, Santa Barbara, the University of Texas at Austin, and Boral Materials, sought to replace cement with another substance to act as a binder that glues together the various ingredients that make up concrete. That substance consisted of fly ash dissolved in a solution, resulting in a product with binding properties similar to those of cement. In this study, titled "**Inorganic Polymers: Novel Ordinary Portland Cement-Free Binders for Transportation Infrastructure,**" once researchers developed that cement-free binder, they also wanted to examine and document how fly ash reacts with certain chemical solutions to better understand how those reactions affect binder performance and production.[5]

For the project "**Service Life Enhancement and Reduction in Carbon Footprint of Highway Structures,**" researchers with the University of California, Berkeley examined how to control cracking in concrete through a hybrid fiber-reinforced concrete, including a hybrid fiber-reinforced concrete composed partly of fly ash.[6]

For the project "**High-Performance, Stress-Relaxing, Cementitious Composites for Crack-Free Pavements and Transportation Structures,**" researchers with Texas A&M University and the Texas Transportation Institute undertook a comprehensive review of carbon nanoflaments and



This three-dimensional image acquired using vertical scanning interferometry helped researchers with the project "Inorganic Polymers: Novel Ordinary Portland Cement-Free Binders for Transportation Infrastructure" see where clusters of fly ash particles occur. © Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles.

carbon nanotubes to develop new models aimed at making these materials better strengthening agents for bridge repairs and crack control.[7]

For the project "**Greatly Increased Use of Fly Ash in Hydraulic Cement Concrete for Pavement Layers and Transportation Structures,**" researchers at Purdue University, Auburn University, the National Institute of Standards and Technology, the National Ready Mixed Concrete Association, and FHWA's Chemistry and Research Laboratories sought to collect performance data and develop best practices for increasing the amount of fly ash to replace portland cement. Fly ash is a byproduct of coal-fired power plants, so recycling fly ash can lead to cost savings.[8]

Research into Alternative Cementitious Materials

A third EAR Program research area has focused on completely replacing the amount of ordinary portland cement in concrete production because manufacturing this cement results in large amounts of carbon dioxide emissions.

For the project "**Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure,**" researchers from the Georgia Institute of Technology, Oklahoma State University, Tourney Consulting, and the U.S. Army Corps of Engineers sought to replace ordinary portland cement with alternative cementitious materials. Alternative cementitious materials, which are primarily used for specialized applications, including minor pavement and bridge repairs, use chemical processes that emit less carbon dioxide. The researchers tested alternative cementitious materials with varying chemical makeups to see how they performed in the laboratory. They looked for the materials' response to typical external and internal threats to concrete, from physical abrasion to progressive alkali silica reactivity deterioration. They investigated the materials' resistance to corrosion and the chemical reactions that might facilitate the deterioration of concrete. They also looked at how the materials performed under freezing and thawing conditions and what shrinkage occurred from drying.[9]

Research into Asphalt Pavements and Binders

A fourth EAR Program research area has focused on the binders of concrete and asphalt. Binders are the glue that sticks aggregate materials, such as sand and stone, together with portland cement to produce concrete, and they are used in producing asphalt for roads.

Through its study "**Improving the Compatibility of Waste Plastic and Asphalt Binder Via Theoretically Justified Identification of Compatible Blends,**" a research team at Louisiana Tech University is investigating how waste plastic could be used to make asphalt. The project aims to examine and develop a computational model that can understand—on a molecular and atomic level—which waste polymers are compatible with which given asphalt binders to optimize the blend's performance. Through this computational model, the researchers aim to provide a foundation for utilizing waste plastic in asphalt pavements on an industrial scale.[10]

In the project "**Developing Frameworks of Performance-Based Asphalt Mix Design,**" a National Research Council (NRC) research associate from North Carolina State University-Raleigh, conducting research at the Turner-Fairbank Highway Research Center, developed performance-related specifications to gauge quality assurance with asphalt mixes. The specifications define desired levels of key materials and characteristics that could be used to predict pavement performance. Findings and data from the research will help develop testing and modeling protocols for performance-based asphalt mix design.[11]

Another NRC research associate, from the University of New Hampshire, developed index parameters that relate to material and structural parameters, helping to identify whether a mixture is prone to fatigue or thermal cracking. Index parameters compare a specialized value to a critical threshold or failure of a material. In the study, titled **"Providing a Performance-Based Asphalt Mixture Design Framework Through Fatigue and Thermal Cracking Index Parameters,"** the researcher used index parameters to gauge the impact of content, gradation, and air voids on asphalt mixtures while monitoring impending thermal or fatigue cracking.(11)

Researchers from Washington State University and Pavement Preservation Systems mixed waste cooking oil with lignin, a byproduct of the paper pulping process, to create a bio-based asphalt binder. To develop the binder, the researchers, in their project titled **"Novel Development of Bio-Based Binder for Sustainable Construction,"** first mixed the waste cooking oil with maleic anhydride at 365 °F and used iodine as a catalyst. This process initiated a chemical reaction in the oil to boost its molecular weight, a process known as polymerization. Next, the team put the lignin through chemical processes to create an epoxy. Because it is more stable at high temperatures, the lignin-derived epoxy makes roads built with the bio-based asphalt binder more resistant to rutting, well-worn depressions, and grooves. Researchers then preblended the polymerized waste cooking oil and lignin, and they mixed that substance with asphalt aggregates in a hot drum to create a "bioasphalt." After curing the mixture for 2 hr, they packed the bioasphalt in a gyratory compactor. The goal of the research was to create a substance that provides as much or more resistance to fatigue, rutting, thermal cracking, and moisture as petroleum-based asphalt.(12)

For the project **"Researching Novel Approaches for Aging Resistant Binder Technologies,"** researchers at Auburn University, in collaboration with Iowa State University researchers and five industry partners, seek to understand additive products that can slow down the aging rate of asphalt. The 3-yr project will examine 6 additives and create an underlying theory for optimizing the use of additives in asphalt. The study will be completed in two phases. The first phase of the research will involve laboratory testing, gauging each additive's performance under various conditions and optimal dosage. The second phase will involve mechanical testing and pavement modeling to see how the additives will impact the life of typical asphalt pavement. At the conclusion of the study, researchers aim to demonstrate at a molecular level how these additives impact asphalt performance and their aging process, creating a deeper understanding of how and why certain additives work.(13)

Research into Coatings

A fifth materials science research area in the EAR Program is the study of how to slow down the deterioration of steel infrastructure through the development of corrosion-resistant coatings.

Researchers with the City College of New York, in their project **"Green Advanced Coatings for Application on Steel Structures and Bridges,"** developed coatings that incorporated nanomaterials, a polyaniline epoxy system with added carbon black, and a nanomaterial-enhanced calcium sulfonate alky system. Both coatings underwent corrosion tests that simulated 20 yr of field exposure to conditions such as temperature changes, salt exposure, humidity, and sulfur-dioxide exposure. The findings helped researchers gain additional insights on incorporating nanomaterials in alkyd and epoxy coatings.(14)

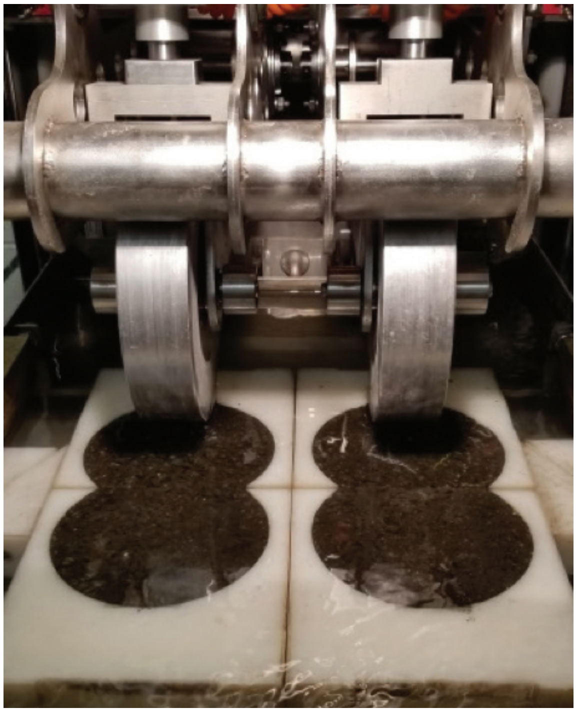
Researchers created a rotary reactor to simulate the production of the hot-mix bio-based binder through mixing aggregates with bioasphalt. © 2017 Department of Civil and Environmental Engineering, Washington State University.

Advancing Early-Stage Materials Science Research into Real-Life Applications

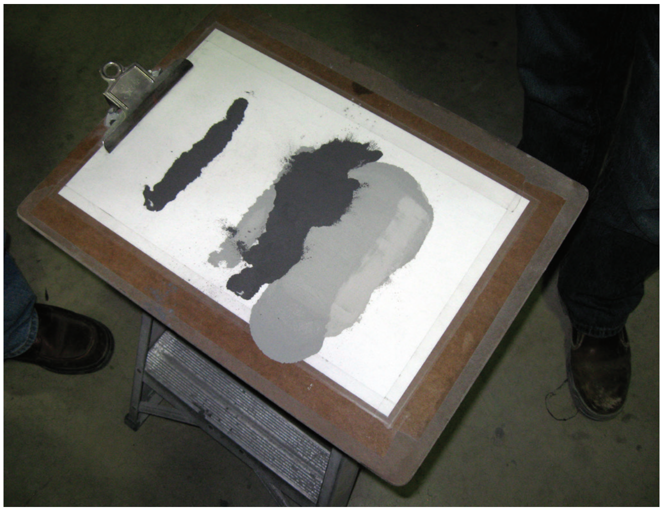
The research is just one step in the development of materials for mass production. Researchers may successfully develop materials that meet performance standards—a chemical binder using a material other than ordinary portland cement may be shown to possess similar durability characteristics, for instance—but producing these materials on a large scale requires multiple trials and outside partners such as companies or other universities.

FHWA's EAR Program is applying technology readiness level assessments to project results and a logic model framework on the materials science portfolio that lays out the production of new materials from research to the stage right before wide-scale production. This process assists in the transition of early-stage results toward useful engineering standards and design that enable the implementation of the new materials.

While the logic model framework employs traditional scientific inquiry as its foundation—formulate a hypothesis, test and observe, analyze findings, develop conclusions, and potentially repeat these steps multiple times—technological developments from other disciplines could produce new and innovative approaches for creating even more opportunities for interdisciplinary research. For instance, by applying the concept of big data, using computers to process large amounts of data and search for shared characteristics or trends, materials modeling research could predict materials' characteristics, paving the way for new formulations.

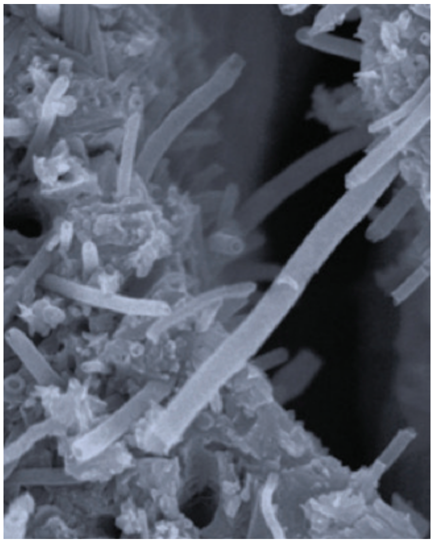


The Hamburg wheel tracking test is conducted on a hot-mix bio-binder to evaluate any permanent deformation. © 2017 Department of Civil and Environmental Engineering, Washington State University.



Fly ash with different carbon content levels. Source: FHWA.

Concrete slump made of an alternative cementitious material (calcium sulfoaluminate). © College of Engineering, Georgia Institute of Technology.



Conclusion

FHWA's EAR Program remains eager to work with university partners and other stakeholders to optimize the latest research tools and processes. These innovations will help develop materials that eventually improve the safety, durability, and efficiency of highway structures and systems.

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Getting Involved with the EAR Program

To take advantage of a broad variety of scientific and engineering discoveries, the EAR Program involves both traditional stakeholders (State DOTs, University Transportation Center researchers, and Transportation Research Board committee and panel members) and nontraditional stakeholders (investigators from private industry, related disciplines in academia, and research programs in other countries) throughout the research process.

Learn More

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

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EAR Program Results

As a proponent of applying ideas across traditional research fields to stimulate new problem solving approaches, the EAR Program strives to develop partnerships with the public and private sector. The program bridges basic research (e.g., academic work funded by National Science Foundation grants) and applied research (e.g., studies funded by State DOTs). In addition to sponsoring projects that advance the development of highway infrastructure and operations, the EAR Program is committed to promoting cross fertilization with other technical fields, furthering promising lines of research, and deepening vital research capacity.

U.S. Department of Transportation
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