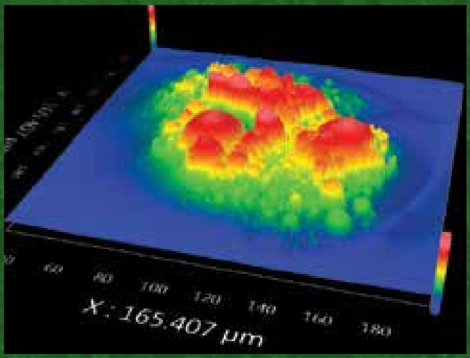
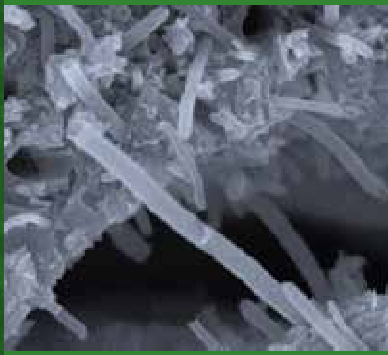
EXPLORATORY ADVANCED RESEARCH

Exploratory Advanced Research Program

Cultivating Materials Science Research to Benefit Surface Transportation Initiatives



U.S. Department of Transportation
Federal Highway Administration

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Introduction

One of the ongoing problems in the construction of bridge structures and highway pavements is that engineers must always grapple with the inevitable deterioration of these structures. Bridges and pavements must bear heavy cars and trucks over a sustained period of time. They also face weather conditions, such as rain and snow or extreme heat and cold, that threaten to wear down materials over time.

To combat the wear and tear that bridges and highways face, researchers are keen to explore how to build structures that are more durable and longer lasting. One way to approach this problem is through materials science. Materials science is a multidisciplinary approach to the scientific study of the production and use of materials through the lenses of chemistry, physics, and engineering.

Breakthrough research in materials science can benefit surface transportation because the innovations developed from this research can be used in construction and repair so that highway bridges and pavements are longer lasting. The Federal Highway Administration's (FHWA's) Exploratory Advanced Research (EAR) Program actively supports research in materials science as a way to address the health of U.S. highway structures and pavements.

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?

Materials science is a cross-disciplinary study of how materials interact with each other. Each material has its own chemical properties, meaning that each has its own weight or mass, chemical composition, and structure. Materials science examines how these factors affect the interaction of these materials. The observations gained from these interactions help researchers and companies develop technology that can produce materials with the desired characteristics.

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; aggregate materials, such as sand and gravel; and water. Researchers are studying how altering the chemical composition of ingredients affect concrete production and concrete's characteristics.

FHWA supports innovation in materials science to provide a greater range of predictable materials for construction and repair of bridges and pavements. For the EAR Program, agency 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 the development of new coatings systems for steel surfaces to improve ease of application and long-term durability.

Another development is the application of microscopic and nanoscale components that can be embedded in structural elements and pavements to help gauge the interior health. These nanoscale components may be able to sense changes in the chemical composition of the materials, or they may be able to 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 research initiatives supported by FHWA's EAR Program have focused on developing new materials that make bridges and highway structures more durable, longer lasting, and impervious to adverse conditions such as extreme temperatures and sustained load bearing.

Building more durable highway bridges and pavements remains a key goal for FHWA. Bridges have a fixed lifespan and must be repaired or replaced as they age.

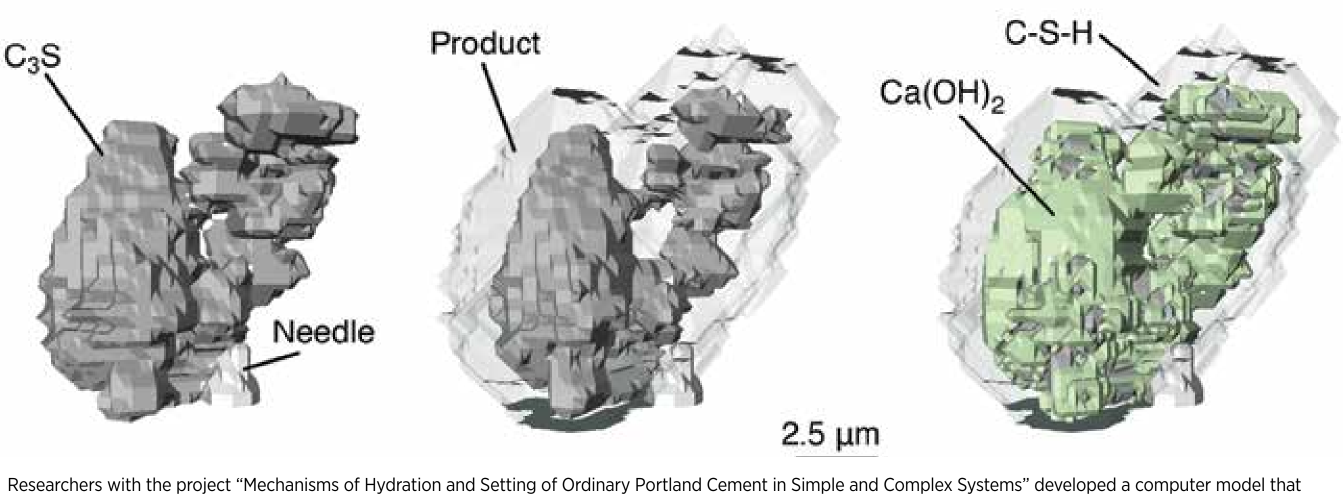
Many of the recent research initiatives supported by FHWA's EAR Program have focused on developing new materials that make highway structures and pavements more durable, longer lasting, and impervious to adverse conditions such as extreme temperatures and sustained load bearing. The research combines techniques developed within chemistry and physics.

Research into Traditional Cement

One research area has been to study concrete at the molecular level. This 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. 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 as they aim to produce concrete that is more durable and cost-effective.



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 hours of simulated hydration. © The American Ceramic Society.

The project "**Predicting Materials Behavior**" 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 of understanding about multiscale modeling at the nanoscale level. They created a digital specimen and digital test technique that used multiscale computerized tomography imaging to observe and analyze materials' behavior and how they act. 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.

For the project "**Nano Material Modeling and Simulation**," 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.

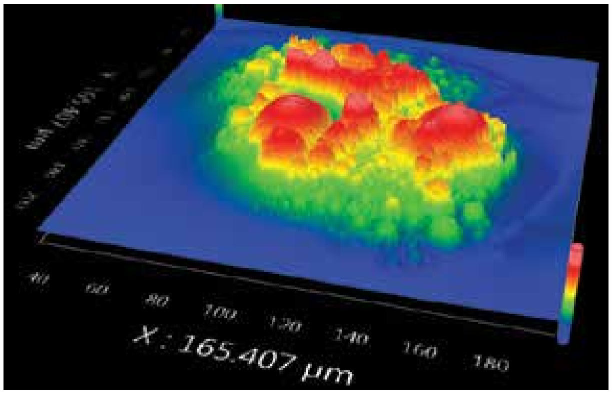
Research into Supplementary Materials

Another research area of the EAR Program 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 "**Inorganic Polymers: Novel Ordinary Portland Cement-Free Binders for Transportation Infrastructure" (FHWA-HRT-18-029)**, researchers at the University of California, Los Angeles, along with partners at the University of California at 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. Once researchers developed that cement-free binder, they also wanted to examine and document how fly ash reacts with certain chemical solutions so that they could better understand how those reactions affect binder performance and production. FHWA is publishing a fact sheet (FHWA-HRT-18-029) with the same title as the research project, which will provide more information and will be available at https://www.fhwa.dot.gov/publications/lists/advancedresearch/pubs.cfm.

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.

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 nanofilaments 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.

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, and so recycling fly ash to serve another purpose can lead to cost savings.

Research into Alternative Cementitious Materials

A third research area has been to replace completely 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 Georgia Institute of Technology, Oklahoma State University, Tourney Consulting, and the Army Corps of Engineers sought to replace ordinary portland cement with alternative cementitious materials. Alternative cementitious materials, which are largely used for specialized applications including small 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.

Research into Asphalt Pavements and Binders

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

For the project "**Developing Frameworks of Performance-Based Asphalt Mix Design**," a National Research Council (NRC) Research Associate from North Carolina State University—Raleigh who conducted research at the Turner–Fairbank Highway Research Center (TFHRC) developed performance-related specifications as a means 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.

For the project "**Providing a Performance-Based Asphalt Mixture Design Framework Through Fatigue and Thermal Cracking Index Parameters**," an NRC Research Associate from the University of New Hampshire who conducted research at TFHRC developed index parameters that relate to material and structural parameters, which would help 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. For this project, the researcher used index parameters to gauge the impact of content, gradation, and air voids on asphalt mixtures, while also monitoring impending thermal or fatigue cracking.

For the project "**Novel Development of Bio-Based Binder for Sustainable Construction**," researchers from Washington State University, along with partner 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 first mixed the waste cooking oil with maleic anhydride at 365°F and used iodine as a catalyst. This 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 hours, 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. FHWA is publishing a fact sheet (FHWA-HRT-18-030) with the same title as the research project, which will provide more information and will be available at https://www.fhwa.dot.gov/publications/lists/advancedresearch/pubs.cfm.

Research into Coatings

A fifth materials science research area 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 years 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.

Researchers created a rotary reactor to simulate the production of the hot-mix bio-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.

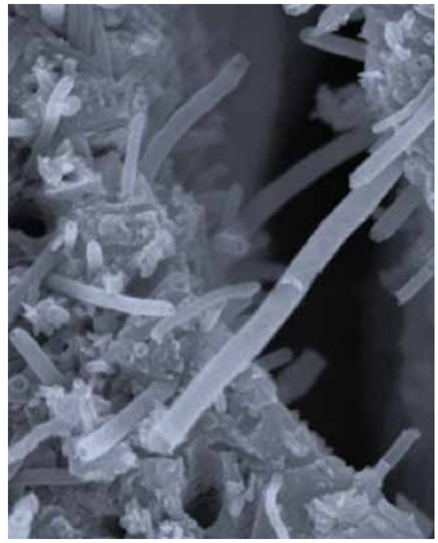
FHWA's EAR Program is applying technology readiness level assessments on project results and a logic model framework on the materials science portfolio that lays out the production of new materials from research to the stage right before wider scale production to assist in the transition of early-stage results toward useful engineering standards and design that enable 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, using the concept of big data, which uses computers to process large amounts of data and search for shared characteristics or trends, materials modeling research could use data to predict materials' characteristics, which could pave the way to 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 on optimizing the latest research tools and processes. These innovations will help develop materials that eventually lead to making highway structures and systems safer and more durable and efficient.

References

Federal Highway Administration. (2015). "Tools for Improving The Sustainability and Durability of Concrete—Modeling Hydration and Performance," Report FHWA-HRT-15-084, Washington, DC. Available online: http://www.fhwa.dot.gov/publications/research/ear/15084/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2012). "Predicting Materials Behavior—Advancing Multiscale Modeling Techniques," Report FHWA-HRT-12-070, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/12070/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2012). "Nano Material Modeling and Simulation: Developing a New Approach to Understanding Material Behaviors by Multiple Length/Time Scale Theories," Report FHWA-HRT-12-029, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/12029/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2013). "Paving The Way for Greener Highways—Extending Concrete's Service Life Through Multiscale Crack Control," Report FHWA-HRT-13-079, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/13079/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2010). "The Exploratory Advanced Research Program Fact Sheet: Crack-Resistant Concrete Maximizing The Service Life of Transportation Infrastructure," Report FHWA-HRT-09-065, Washington, DC. Available online: http://www.fhwa.dot.gov/publications/research/ear/09065.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2010). "Benefits of High Volume Fly Ash: New Concrete Mixtures Provide Financial, Environmental, and Performance Gains," Report FHWA-HRT-10-051, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/10051/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2015). "Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure," Report FHWA-HRT-16-017, Washington, DC. Available online: http://www.fhwa.dot.gov/publications/research/ear/16017/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2017). *Exploratory Advanced Research Program Research Associates Program 2016*, Report FHWA-HRT-17-023, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/17023/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2017). *Exploratory Advanced Research Program Research Associates Program 2016*, Report FHWA-HRT-17-023, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/ear/17023/index.cfm, last accessed October 26, 2018.

Federal Highway Administration. (2013). "Greener Protection for Steel Bridges—Testing Nano-Enhanced Corrosion-Resistant Coatings," Report FHWA-HRT-13-064, Washington, DC. Available online: http://www.fhwa.dot.gov/publications/research/ear/13064/index.cfm, last accessed October 26, 2018.

Notes

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 department of transportation researchers, 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 on upcoming events.

EAR Program Results

The EAR Program strives to develop partnerships with the public and private sectors because the very nature of the EAR Program is to apply ideas across traditional fields of research and stimulate new approaches to problemsolving. The program bridges basic research (e.g., academic work funded by National Science Foundation grants) and applied research (e.g., studies funded by State departments of transportation). In addition to sponsoring EAR Program 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.

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