Research on Concrete Applications for Sustainable Transportation

RE-CAST

MISSOURI S&T

Vol. 4 :: Issue 1 :: WINTER 2017

In this issue:

CONSORTIUM MEMBERS:

Missouri University of Science and Technology

University of Illinois at Urbana-Champaign

Rutgers, The State University of New Jersey

University of Miami

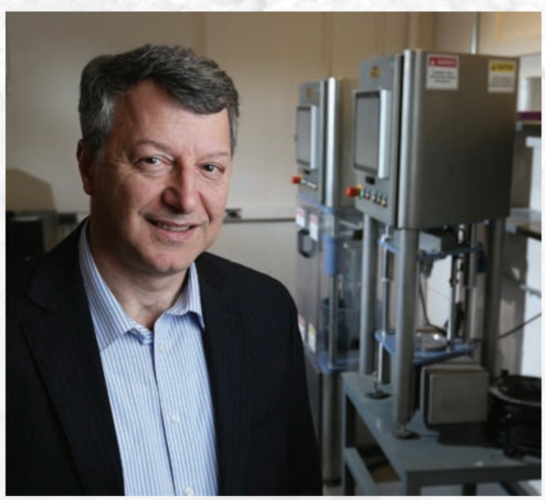
Southern University and A&M College

Director's Message

As the new year begins, we at RE-CAST would like to wish everyone a Happy and successful New Year. Hopefully all our readers enjoyed the holidays are are back to the office/lab refreshed and ready to explore new ideas.

We have three research project updates to report on and invite any questions our readers may have about them. Our research team's contact information is available on our webpage and we invite your feedback.

We co-hosted a joint online webinar with the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC) and the ACI Alaska Chapter on Nov. 9, 2016. Dr. Antonio Nanni of RE-CAST presented "The Role of Cementitious Materials in the Next Decade." We also had Dr. Raissa Ferron from the University of Texas at Austin give an interesting webinar on "Engineering smart, stimuli-responsive cementitious composites." We invite you to visit our webinar library for additional details and sign up for our upcoming webinars.



We are also happy to share with you our 2016 Student of the Year, Matthew Hopkins, a Ph.D. candidate at Missouri S&T. More details about this award and Matthew can be found on the following pages.

Kamal H. Khayat
RE-CAST Director

OUTREACH/WORKFORCE DEVELOPMENT

2016 RE-CAST Student of the Year: Matthew Hopkins

2016 RE-CAST Outstanding Student of the Year, Matthew Hopkins (left) pictured with former U.S. Secretary of Transportation, the Honorable Norman Mineta (middle) and RE-CAST Director and Matthew's advisor, Dr. Kamal H. Khayat (right)

For the past 24 years, the U.S. Department of Transportation (USDOT) has honored an outstanding Student from each University Transportation Center (UTC) at a special ceremony held during the Transportation Research Board (TRB) Annual Meeting. This year, the RE-CAST University Transportation Center selected Mr. Matthew Hopkins as its Outstanding Student of the Year. He was recognized at the 26th Annual Outstanding Student of the Year Awards ceremony that took place as part of the Council of University Transportation Centers (CUTC) annual banquet on Saturday, January 7, 2017 in Washington, D.C. Mr. Hopkins was selected for his outstanding academic performance as well as the technical merit and national importance of his research. Additional information on Mr. Hopkin's qualifications for this award are outlined on the following page.

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OUTREACH/WORKFORCE DEVELOPMENT

Student of the Year Award *(continued)*

Matthew Hopkins is a Ph.D. Candidate in the Department of Civil, Architectural and Environmental Engineering at Missouri S&T. His research includes the material design of high-strength self-consolidating concrete (HS-SCC) and its performance in potential applications related to transportation infrastructure. The material design includes experiment optimization of mixture proportions and the investigation of the affect of internal curing on performance. Mr. Hopkins is researching the rheology during casting and structural performance of large-scale elements made with HS-SCC. In 2016, Matthew completed a statistical design experiment to optimize the mixture proportions for HS-SCC. He is currently analyzing the data to model the effect of mixture proportions on fluidity and mechanical properties HS-SCC and plans to publish his results in the near future.

Matthew received his bachelor's degree in Civil Engineering from Missouri S&T in 2011. He then received the Chancellor's Fellowship to pursue his master's degree at Missouri S&T. His master's research focused on the structural performance of fiber-reinforced polymer (FRP) sandwich panels for bridge decking. He received his master's degree in Civil Engineering in 2014 and the Chancellor's Fellowship a second time to pursue his doctorate at S&T.

His adviser, Dr. Kamal H. Khayat, believes that the Student of the Year award affirms Matthew's contributions to RE-CAST's themes on high performance concrete with adapted rheology and the valorization of recycled materials in concrete construction. The award recognizes the high caliber of our students and our congratulates goes to Matthew.

LEADERSHIP SPOTLIGHT

Director to receive national award for concrete innovation

Dr. Kamal H. Khayat, RE-CAST Director, will be honored with the ACI Foundation's Jean-Claude Roumain Innovation in Concrete Award in March 2017. The award will be presented March 26 during the ACI Spring 2017 Concrete Convention and Exposition in Detroit.

He received the award for *"over 25 years of research, teaching, innovation and leadership contributing to the advancement of self-consolidating concrete; and for the relentless pursuit of knowledge transfer by organizing numerous conference covering the science, performance, design and testing standards of self-consolidating concrete*."

FEATURED PROJECT

Recycled concrete used to create novel foamed materials

- David Lange, Ph.D., Professor of Civil Engineering, University of IL at Urbana-Champaign
- Yu Song, Kate Hawkins, and Jamie Clark, University of IL at Urbana-Champaign

Research at the University of Illinois at Urbana-Champaign (UIUC) on recycled concrete has focused on finding applications for fine particles produced by concrete crushing operations. While recycled coarse aggregate is accepted for pavement base layers and even new pavement concrete, the fines pose significant difficulty due to their high variability, high water demand, and lower strength potential. The fine particles, however, are well-suited for controlled low strength materials that can be used for flowable fill and other low strength applications. Building on that idea, researchers at UIUC are exploring a new niche for recycled fines – foamed materials.

"Cellular solids are nature's equivalent of the I-beam," is an ingenious metaphor by Michael Ashby. For a given amount of material, the structural capacity can be significantly optimized if the material is cellular instead of solid. The effectiveness of cellular structures is widely confirmed in nature—animal bones and plant stems are all cellular solids. As a result, man-made cellular materials have increasingly gained attention from researchers.

Foam concrete is a lightweight construction material with such cellular structures. It is generally classified as a type of low-density controlled low-strength material (LD-CLSM) according to ACI 229. Due to its high porosity, the density of foam concrete ranges from 25 to 100 pcf, leading to a low strength ranging between 30 and 1500 psi—significantly weaker than conventional concrete. These materials have potential uses as crushable low-strength and energy-absorbing elements, and their use in value-added applications is a strong step toward sustainable construction practices.

Early work at UIUC has developed a mixing protocol to produce foam concrete with desirable robustness for both fresh and hardened properties. Several testing approaches and methods have been proposed to characterize the unusual material properties of foam concrete. For instance, the conventional mechanical testing approaches are not applicable to measure Young's modulus of foam concrete because the material is so fragile. Instead, resonance frequency meothds (ASTM C215) are much more successful to measure Young's modulus. Recent testing results prove that the effects of various mixing factors and concrete admixtures on the material properties can be evaluated with the proposed testing system.

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Recycled concrete used to create novel foamed materials (*con't*)

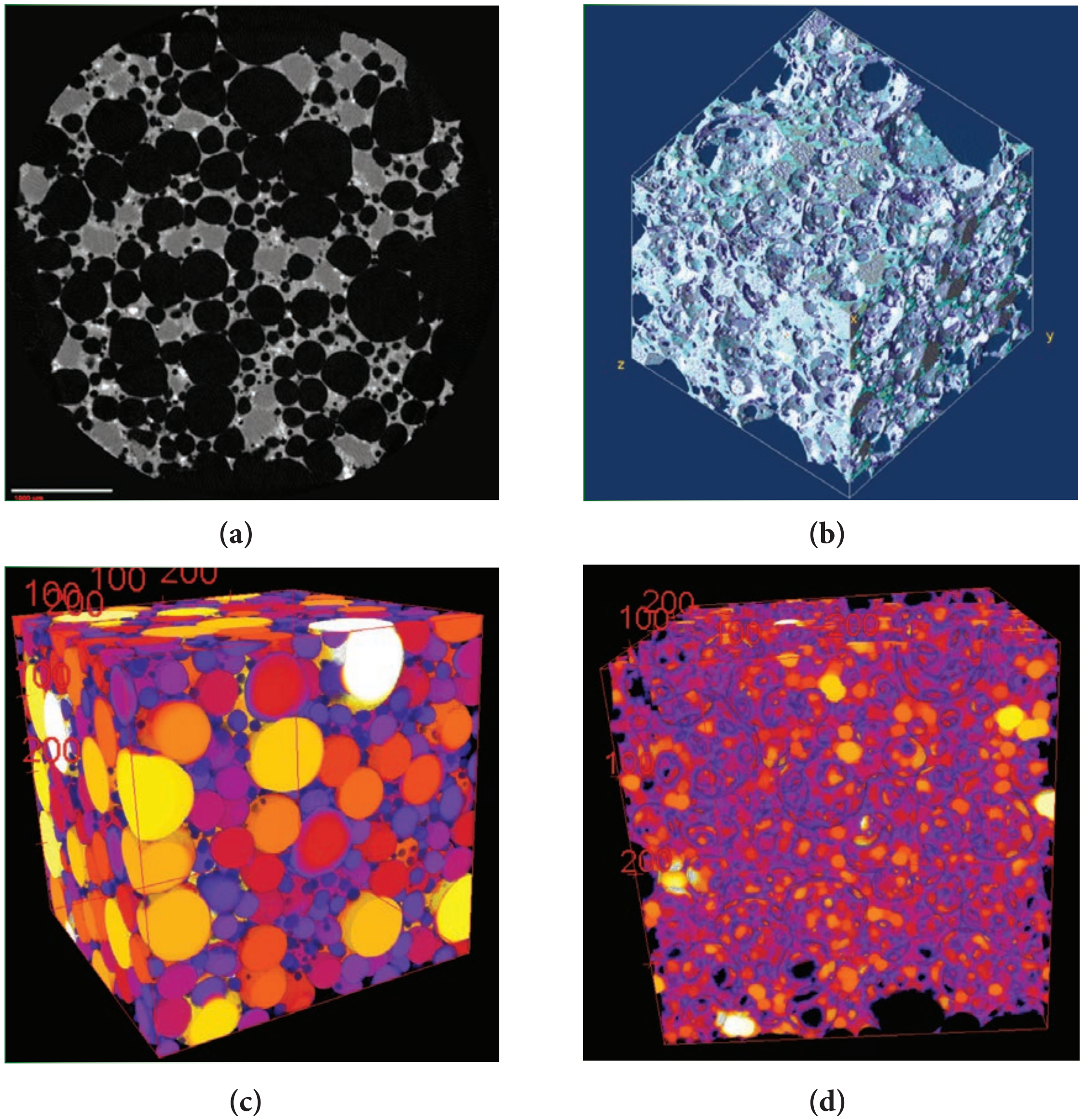

Figure 1. 3D renderings of a foam concrete sample based on micro-CT scans: (a) a single CT scan; (b) reconstructed model of the scanned section; (c) thickness model of the embedded voids; (d) thickness model of the cement skeleton. For (c) and (d), the warmer color indicates larger void size and greater strut thickness, respectively.

To establish the constitutive relationship of foam concrete, several additional testing techniques have been adopted to characterize the void structure on the microstructural level and to investigate the mechanical response on a macro scale level. The geometric features of the actual 3D void structure are characterized using micro-CT (see **Figure 1**). The model is also 3D printed as to render a more intuitive understanding of the complex void system (see **Figure 2**).

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Recycled concrete used to create novel foamed materials (*con't*)

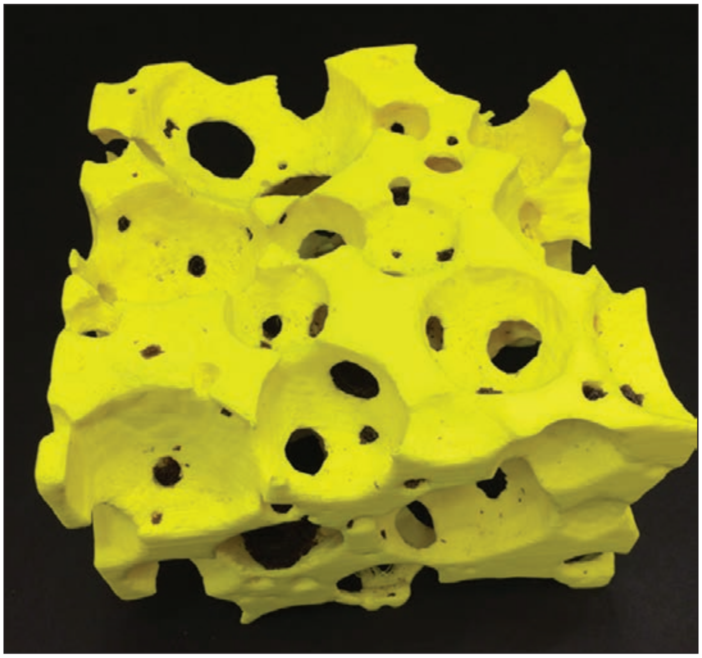

Figure 2. A physical 3D printed model of the foam concrete sample shown in Figure 1. The model has a magnification scale of 150.

On the macro-scale, a digital image correlation (DIC) test is used to assist the study on material deformation under indentation. A sequence of images showing the strain distribution during the indentation is given in **Figure 3**, in which the indenter proceeds progressively deeper into the sample. Localized material densification is observed under the indenter, gradually leading to the formation of a passive cone, which moves downward with the indenter like a rigid body.

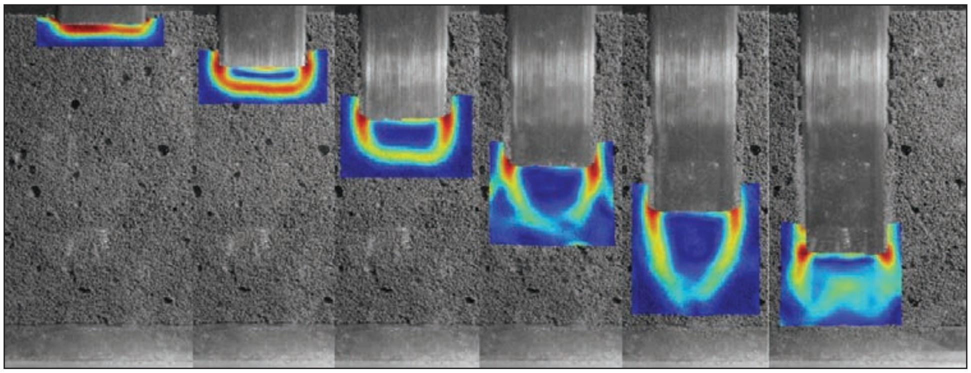

Figure 3. Instantaneous strain plots for the densified foam concrete under the indenter at various depths, red indicates high intensity, and blue indicates low intensity.

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Recycled concrete used to create novel foamed materials (*con't*)

(a)

(b)

Figure 4. Formation of the passive cone under indentation—a layered accumulation of the densified material: (a) original shape of the foam concrete sample; (b) the same sample after indentation.

This resonates with the result of an analysis of the material deformation demonstrated in **Figure 4**. A careful inspection on these observations suggests that two failure modes coexist under the indenter: the material at the bottom is crushed due to pure compression; however, shear failure dominates at the sides of the passive cone.

Given that the basic material properties and a deeper insight into the constitutive relationship can be obtained, the mechanical behavior of foam concrete will be studied using advanced finite element modeling approaches as the next step. This project will advance an innovative use of recycled fines that would otherwise be discarded in a landfill, and in this way the research will contribute to sustainable construction practices. The Illinois graduate students leading this work are pictured in **Figure 5**, and they are working under the supervision of Prof. David Lange.

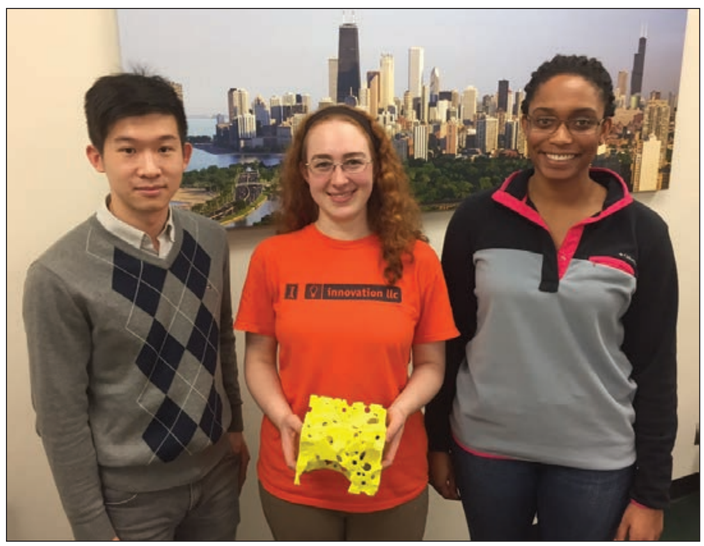
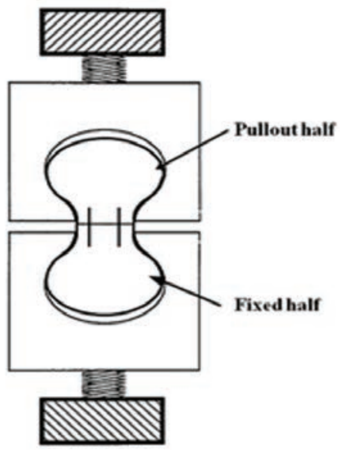


Figure 5. Yu Song, Kate Hawkins, and Jamie Clark are graduate students working on foamed cements made with recycled fines. Jamie used X-ray computed tomography to capture a 3-D image of the microstructure of material fabricated by Yu. Kate converted the CT data and used a 3-D printer to produce the yellow model that is 100X larger than the actual material.

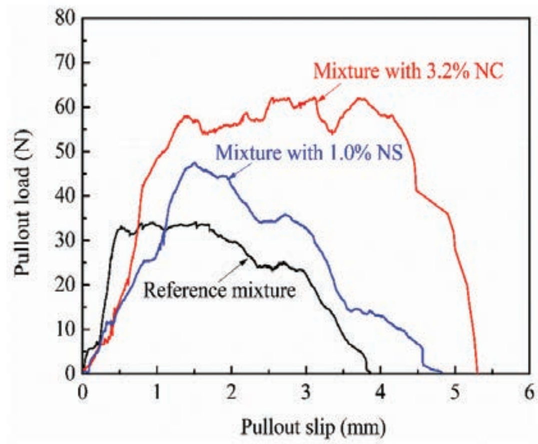
FEATURED PROJECT

Use of nano-materials to enhance stress transfer efficiency at interfacial transition zone in UHPC

- Zemei Wu, Ph.D. candidate, Civil Engineering, Missouri S&T
- Kamal H. Khayat, Ph.D., Civil Engineering, Missouri S&T
- Caijun Shi, Ph.D., Professor, Hunan University, China



(a) Pullout test



(b) Fiber pullout load-slip curves

Figure 1. Fiber pullout load-slip curves of UHPC matrix after 28 d standard curing

Cement-based material is a multi-phase material, including nano, micro, meso, and macro phases. Its macro-properties are dominated by the microstructure development of hydration products, especially C-S-H at the nano-scale. Ultra-high performance concrete (UHPC) is a new class of construction material that exhibits superior durability, tensile ductility and toughness. The performance of UHPC is affected by the intrinsic characteristics of the cementitious matrix, fiber properties, and interfacial transition zone (ITZ) between the matrix and fibers. Use of nano-particles in cement-based materials can lead to significant enhancement in homogeneity, improvement in microstructure, and increase in mechanical properties and durability of this novel material.

The quality of fiber-matrix ITZ in UHPC is closely correlated to the stress transfer efficiency between the matrix and fiber and eventually mechanical properties. This study investigated the microstructure, fiber bond properties, and flexural properties of UHPC made with either 3.2% nano-$CaCO_3$ (NC) or 1% nano-SiO_2 (NS). The dosages for such nano-materials were determined based on rheological testing. The fiber bond properties were evaluated using dog-bone pullout test (**Figure 1a**). Three-point bending tests were conducted on 40 × 40 ×160 mm prisms to investigate the flexural properties of UHPC with 2% micro steel fibers. The NC is shown to be promising for improving the mechanical properties of UHPC.

The pullout load-slip relationships after 28 d standard curing of four embedded fibers in UHPC matrix are compared in **Figure 1b**. All mixtures were prepared with 20% silica fume, by total mass of binder.

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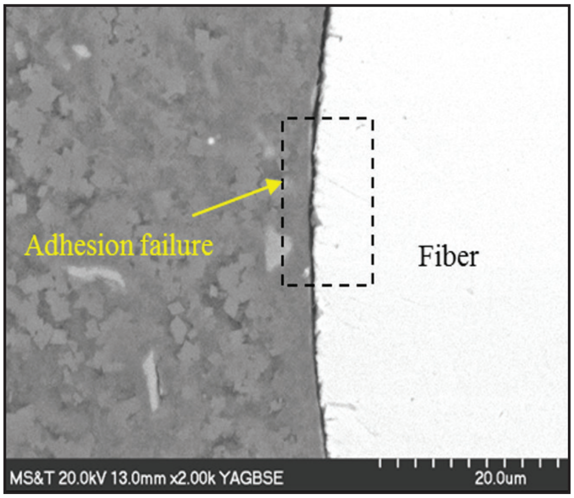
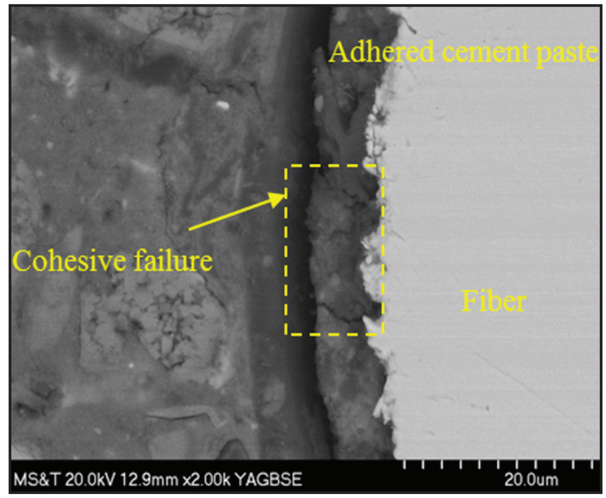
Nano-materials to enhance stress transfer efficiency *(con't)*



(a) ITZ failure at reference matrix and fiber interface



(b) ITZ failure at UHPC matrix with NC and fiber interface

Figure 2. SEM images of samples with an embedded fiber after pullout testing

The use of nano-materials significantly improved the fiber-matrix bond properties. The peak loads of the UHPC with NC or NS were increased by approx. 80% and 40%, respectively, in comparison with the reference mixture without nano-materials. Flexural toughness was enhanced by 150% and 30%, respectively. Figure 2 shows the scanning electronic microscopy (SEM) images of samples with an embedded fiber after pullout testing. It can be observed from **Figure 2a** for the sample without nano-materials that cracking occurred very close to the steel fiber. This was different from the sample with NC, in which cracking occurred within the bulk paste; 4 to 5 µm paste is found adhered to the fiber (**Figure 2b**). Therefore, the incorporation of NC transformed the adhesive failure into cohesive failure with greater bond strength.

Figure 3 shows flexural load-deflection curves of UHPC with 2% steel fibers for mixtures with and without nano-particles. The fluidity of the three UHPC mixtures was kept at 220 mm to ensure self-consolidation. The mixture with NC exhibited the best flexural properties, followed by that with NS. This corresponds to the observation made on the fiber pullout properties. The peak loads of mixtures with NC or NS were increased by 30% and 10%, respectively. The level of improvement was lower than that of the fiber bond strength, which can be due to random fiber orientation in the UHPC matrix. Based on the results obtained, the use of nano-materials along with the silica fume can significantly enhance fiber bond and flexural properties of the UHPC. The use of 3.2% NC led to greater enhancement of stress transfer between the matrix and fibers and thus greater mechanical properties than NS.

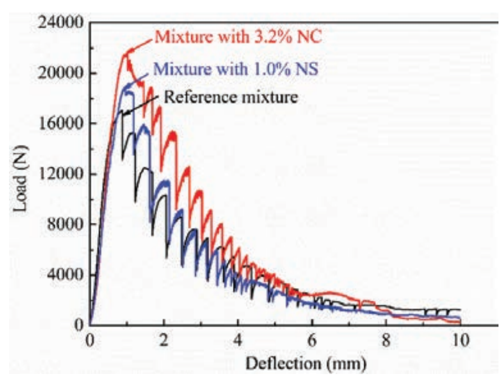


Figure 3. Flexural load-deflection curves of UHPC prisms with and without nano-materials after 28 d of standard curing

FEATURED PROJECT

A Case Study after Two Decades of Service: GFRP Reinforced Box Culvert

- Omid Gooranorimi, Ph.D. Student, University of Miami
- John J. Myers, Ph.D., Dept. of Civil Enigneering, Missouri S&T
- Antonio Nanni, Ph.D., Professor of Civil Engineering, University of Miami

Figure 1. Old (left) and new (right) Walker Bridge

Corrosion-resistant glass fiber reinforced polymer (GFRP) composite bars are emerging as an alternative for traditional steel reinforcement in concrete structures exposed to aggressive environments, such as bridges and box culverts. While GFRP eliminates the problems related to corrosion of steel reinforcement, its long-term behavior in commercial applications warrants field study validation. A box culvert bridge consisting of precast concrete units entirely reinforced with GFRP bars (constructed in 1999, on Walker Avenue in the City of Rolla, Missouri) was chosen as a case study. It replaced the original bridge that was built in the early 1980's and diagnosed unsafe to operate due to excessive corrosion of encased steel pipes (**Figure 1**).

Material samples were extracted from different locations of the box culvert and analyzed to monitor possible changes in GFRP and concrete after more than sixteen years of service (**Figures 2 and 3** shown on next page). Initially, carbonation depth, pH and chloride diffusion measurements were performed on concrete cores surrounding the GFRP bars. Subsequently, scanning electron microscopy (SEM) imaging and energy dispersive X-ray spectroscopy (EDS) were conducted on GFRP samples to monitor any microstructural degradation or change in chemical compositions. In addition, glass transition temperature (Tg) of the resin and fiber content were determined, and results were compared with pristine samples produced in 2015. Results from the concrete tests were consistent with expected values corresponding to the type and age of the structure.

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A Case Study after Two Decades of Service (con't)

Figure 2. Sample extraction from box culvert units

Figure 3. GFRP coupons extracted from the concrete cores

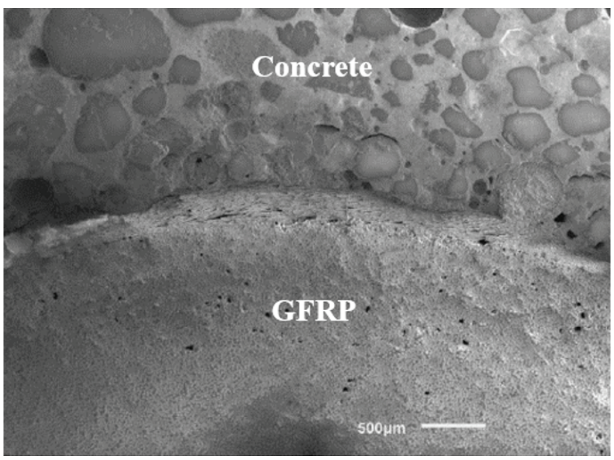


Figure 4. SEM Image of Concrete to GFRP Interface

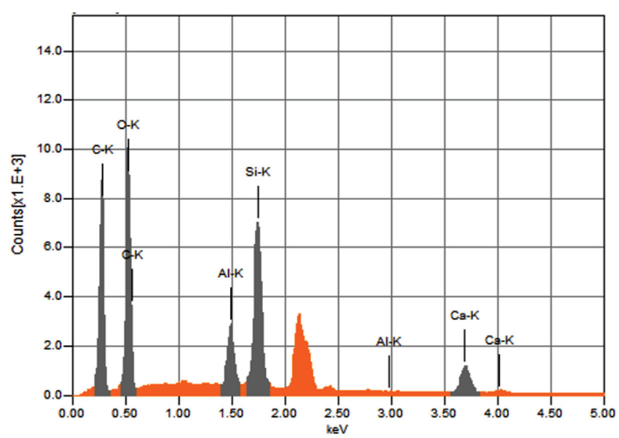


Figure 5. Result of EDS analysis performed on GFRP samples after 16 years of service

SEM images and EDS test (**Figures 4 and 5**) did not show any signs of GFRP microstructural deterioration. Moreover, Tg and fiber content of GFRP coupons were comparable to values from samples tested in 2015. The results of this study validate the notation that GFPR material properties are maintained during two decades of service. Hence, using GFRP internal reinforcement in box culverts eliminates corrosion problem, reduces the long-term maintenance costs and increases the service life of the structure. To learn more detailed information about efforts in this area, the following RE-CAST final report on a similar effort in Texas may be referenced:
Technical Report #00042134-04-103A

Special Acknowledgements: the assistance of Missouri S&T CIES Sr. Technical Staff **Mr. Jason Cox** to extract samples and **Mr. Doug Gremmel** from Hughes Brothers in Stewart, NE is greatly appreciated.

WEBINAR SERIES

Visit our Webinar Library at: recast.mst.edu/webinars

November 17, 2016

Presenter: Dr. Raissa Ferron, Assistant Professor

University of Austin at Texas

"Engineering smart, stimuli-responsive cementitious composites"

November 9, 2016

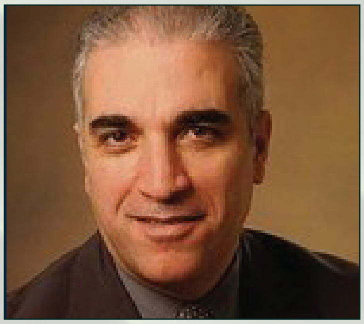
RE-CAST Presenter: Antonio Nanni

Professor of Civil Engineering, Univ. of Miami

CESTiCC, RE-CAST and the Alaska Chapter of ACI present:

"The Role of Cementitious Materials in the Next Decade"

- Joint webinar offered with CESTiCC and Alaska Chapter of ACI



October 11, 2016

Presenter: Hani Nassif, Professor of Civil Engineering

Rutgers University

"Structural Health Monitoring (SHM) of Corrosion Potential in Concrete Bridge Decks"

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