Ushering in High-Strength Reinforcement

ACI Foundation and the industry-wide effort to raise the limits on specified strengths in reinforcement

by Victoria K. Sicaras on behalf of the ACI Foundation

In 2014, the ACI Foundation joined forces with the Charles Pankow Foundation and other industry organizations to fund the research necessary to introduce a new technology to codes: high-strength reinforcement. The research initiative was supported by the ACI Foundation—a wholly owned subsidiary of the American Concrete Institute that invests in research, innovation, and scholarships to advance the concrete industry—and its three councils: the Concrete Research Council, the Concrete Innovation Council, and the Scholarship Council. This article explains how the initiative stretched across the reinforced concrete sector to bring significant changes to ACI 318, "Building Code Requirements for Structural Concrete."

As buildings get taller and are required to resist higher seismic forces, using higher-strength reinforcement seems a natural solution. After nearly 50 years of limiting the yield strength of reinforcement to Grade 60 in seismic applications and Grade 80 in general, ACI 318-19, "Building Code Requirements for Structural Concrete",[1] raised the limits on specified strengths. The last comprehensive update related to reinforcing bar strength was made in 1971.[2]

"This was a generational move—a move forward in the industry in a large way that will make a huge difference in building construction," said Jack Moehle, FACI, who served as Chair of ACI Committee 318, Structural Concrete Building Code, for the 2019 Code cycle.

The 2019 standard now allows up to Grade 100 reinforcement for some special seismic systems and no longer allows Grade 40 reinforcing bar to be used for flexural reinforcement in seismic applications. Shear walls can employ reinforcing bar in Grades 60, 80, or 100. Special moment frames can use Grades 60 or 80.

These changes are thanks to an industry-wide research collaboration among funders, researchers, steel manufacturers, and ACI code committees, for which the ACI Foundation provided substantial funding. The Charles Pankow Foundation (CPF) served as the main funder and project management entity while other major funders included the Concrete Reinforcing Steel Institute (CRSI), Precast/Prestressed Concrete Institute (PCI), and Magnusson Klemencic Associates (MKA) Foundation.

"This has been an incredibly important initiative that the ACI Foundation is pleased to support," said Ann Masek, ACI Foundation Executive Director. "It perfectly aligns with our mission to make strategic investments in ideas, research, and people to create the future of the concrete industry."

The research effort necessitated the participation of several industry players from across the reinforced concrete sector. "The scope of this endeavor was bigger than one organization could take on. We knew that we'd be able to move faster and have a bigger impact if we joined forces and brought everybody to the party," Moehle said.

"We found a real superpower in industry collaboration," added Anne Ellis, Executive Director of CPF, which provides leadership and catalytic funding to support game-changing research in the architecture, engineering, and construction (AEC) industry. "Our partners include producers of the product who provide the materials for testing as well as designers, contractors, and educators. We have representatives from across the ecosystem."

To date, 15 research projects have been completed, and more are expected to launch as part of the combined industry effort. Completed projects have demonstrated acceptable performance of members of special seismic systems reinforced with ASTM A706/A706M Grade 80 reinforcement and ASTM A706/A706M-equivalent Grade 100 reinforcement.

Assessing the Need

Typically, any reinforcing bar with a yield strength greater than 60 ksi (414 MPa) is considered high-strength reinforcement (HSR). When higher-strength steel is used, fewer reinforcing bars may be needed. This translates to less bar congestion, which allows for simpler, more efficient reinforced concrete construction. For example, less congestion leads to easier cage fabrication and concrete placement. Such improvements generally result in fewer defects and less rework. Additionally, when less material is needed, labor and costs are reduced throughout the supply chain and well beyond the delivery of the structure.

"HSR makes it possible to cost-effectively and more efficiently build some elements that were getting to be tough to construct with the lower-grade reinforcements," Moehle explained. "Ultimately, we'll have more efficient buildings in terms of materials used. And that's important from an environmental perspective."

However, industry adoption of high-strength grades depends on codification. Before the 2019 Code cycle for ACI 318, U.S. building codes limited reinforcing bar strength based on decades-old research and the assumption that most reinforcement used in concrete construction in the United States is Grade 60.

"Grade 60 was introduced in the 1950s, and it took 20 years to become standard practice in the United States. Just think about all the innovations in advanced materials, including steel, since that time," Ellis said.

By the early 2000s, progress in metallurgy had resulted in the production of reinforcing bar almost twice as strong as it was several decades ago. Reinforcement with a yield strength greater than 75 ksi (517 MPa) became more readily available—including Grades 80, 100, and 120. Implementation of these grades in U.S. projects could not be accomplished without changes to the Code—and the documented research to justify those changes.

Sustaining the reinforced concrete industry depends on the adoption of new technologies. Moving to high-strength reinforcing steel takes advantage of an existing technology with minimal adoption due to impediments in the Code. Resolution of those impediments allows the technology to be readily adopted, considering the only recognizable change will be in the metallurgy of the steel. All other processes to construct using this technology will remain essentially unchanged

In 2012, CPF began investigating the research needs associated with incorporating reinforcing steel stronger than 60 ksi into ACI 318. The investigation was prompted by interest on the part of structural engineering practitioners, structural concrete constructors, and key academic researchers who believed higher-strength reinforcing bars could provide a significant benefit to the industry.

"U.S. engineers were seeing high-strength reinforcing bar being used overseas. They saw the potential to help simplify reinforcing bar detailing and placement as well as to save time and improve jobsite safety. In conversations with other structural engineers at ACI, we found a collective interest in overcoming the technical barriers in the United States to allow for market acceptance and adoption of the high-strength reinforcing bar," Ellis said.

High-strength reinforcing bar also was becoming the material of choice in certain applications in the United States, particularly on the West Coast for seismic design, Ellis added. This was due to the reduction in the number of bars needed in comparison with using Grade 60 bars.

A concentrated effort across the reinforced concrete sector was needed to provide documentation of the behavior and performance of structural elements reinforced with higher-strength steel. This type of undertaking had not previously been done, and the results were expected to move reinforced concrete design and construction to a new level.

Taking the Lead

The coordinated research effort was spearheaded by Mark Perniconi, then-Executive Director of CPF. Ellis—ACI Past President (2013-2014)—took over the mantle when she became Executive Director of CPF in 2018.

CPF's initial investigative efforts involved informal meetings with an expert panel that included several industry leaders—including Moehle and CSRI's then-Vice President of Engineering Mike Mota, FACI. See the sidebar for a list of key early contributors who helped initiate the HSR research movement.

Moehle also credits Ron Klemencic, FACI, for being the "mover and shaker" who pulled ideas together. Klemencic, a CPF Director, heads the leadership team at the MKA Foundation, a nonprofit funded by MKA that engages and invests in nonproprietary research to advance the engineering industry.

"Buy-in was required from so many people. We had to be committed to moving things fast if we wanted to get research results out and reviewed in time for the 2019 Code cycle," Moehle said.

What followed was the commissioning of several research projects studying the technical feasibility of using higher-strength bars as well as developing a technical definition of the HSR product. At the same time, CPF engaged steel reinforcing bar producers to evaluate the technical and financial feasibility of making high-strength bars commercially available.

"It was so important to get all the parties in the same room at the same time to make it plain what designers needed versus what producers could provide," Moehle said. "From there came the process of meeting in the middle to get a safe, economical product that we could add into the Code."

By mid-2013, the initial studies confirmed the technical feasibility of using HSR in design. In addition, reinforcing bar producers verified that higher-strength bars could be manufactured and made available through normal distribution channels.

An unrelated effort funded by the National Institute of Standards and Technology (NIST) confirmed the feasibility of using HSR in seismic applications (NIST GCR 14-917-30, "Use of High-Strength Reinforcement in Earthquake-Resistant Concrete Structures"[3]). The report also showed a cost savings of about 4% of the cost of the concrete structure when using Grade 80 reinforcement instead of Grade 60.

Developing a Research Roadmap

With technical feasibility and manufacturing capability confirmed, the next task was to determine the applied research and engineering studies necessary to support an update to ACI 318.

In 2013, CPF commissioned the Applied Technology Council (ATC) to create a roadmap for the use and applications of HSR and development of Code-change proposals. The roadmap, referred to as the ATC-115 Project,[4] identified about 40 provisions in ACI 318 covering more than 80 topics in need of documentation for potential updating. It also identified research and knowledge gaps, establishing a plan to provide the data needed to support Code changes.

"The roadmap has been invaluable," Ellis said. "We've used it to prioritize the topics that we need to investigate so we could start working down a list."

Upon the completion of the roadmap in 2014, the ACI Foundation joined the initiative as a research funding partner, and according to Moehle, the roadmap has been instrumental in executing fast-track funding. "It pinpointed what we needed to study and what we did not, so when a researcher proposed a topic, we knew whether it was going to pay off. Having the ability through a funding agency or several funding organizations to make quick decisions about proposals matters," he explained.

Research

The research roadmap identifies 80 research projects, and 18 have so far been completed or are in progress (see the sidebar on HSR Projects). Given the number of Code provisions affected, the scope of the research effort includes extensive validation of design requirements to assure reliable safety and performance of structures. The overarching goal is to provide experimental and applied research data acquired in both nonseismic and seismic applications.

The research projects build on each other, with the first projects revisiting the fundamentals. Initial projects included a revisit of research materials from the metallurgists who develop material standards on reinforcing bar yield strength and from reinforcing steel producers with expertise in metallurgy, the manufacturing process, and material standards development. Subsequent projects have tested the low-cycle fatigue properties of HSR and requirements for bar development and lap splices—and have demonstrated applications in foundations, structural walls, coupling beams, and special moment frame beams and columns.

An industry advisory committee of key stakeholders is established for each project to keep all parties informed as projects progress, Moehle said. The advisory committees meet at ACI conventions twice a year and as needed the rest of the year. Principal investigators present what they've learned at these meetings, which are attended by Chairs of ACI Committee 318 subcommittees. The research results are shared with subcommittees and used to inform changes to ACI 318.

"From the code-writing side, it is important to make sure the studies get done—and that the producers of the material and the researchers who conduct the studies and the engineers who would have to implement the designs work

Key Early Contributors to the HSR Research Movement

The following individuals served on committees or as consultants to help develop the Charles Pankow Foundation's research roadmap in 2013-14:

Project Management Committee

Dominic J. Kelly, Simpson Gumpertz & Heger (Project Technical Director)
David Darwin, University of Kansas
David C. Fields, Magnusson Klemencic Associates
Robert J. Frosch, Purdue University
Andrés Lepage, University of Kansas
Joseph C. Sanders, Charles Pankow Builders
Andrew S. Whittaker, University at Buffalo, SUNY

Project Review Panel

Wassim M. Ghannoum, The University of Texas at San Antonio
S.K. Ghosh, S.K. Ghosh Associates
Ramon Gilsanz, Gilsanz Murray Steficek
James O. Jirsa, The University of Texas at Austin
Mike Mota, CRSI
Thomas C. Schaeffer, Structural Design Group
Loring A. Wyllie Jr., Degenkolb Engineers

Special Consultants

Jack Moehle, University of California, Berkeley
Conrad Paulson, Wiss, Janney, Elstner Associates
Robert Risser, CRSI

HSR Projects—Completed and in Progress

Project	Principal investigator(s)	Funding organization(s)	Completion date
The Impact of High-Strength Reinforcing Steel on Current Design Practice	Laura Lowes, University of Washington	CPF	2013
Development of a Roadmap on the Use of High-Strength Reinforcement in Reinforced Concrete Design (ATC-115 Project)	ATC	CPF	2014
Anchorage of High-Strength Reinforcing Bars	David Darwin, University of Kansas	CPF, CRSI	2014
Assessment of Yield Stress Measurement Methods for Reinforcing Bars	Conrad Paulson, Wiss, Janney, Elstner Associates	ACI Foundation, CPF, CRSI	2014
Development of Tentative Specification for High-Strength Reinforcing Bar	Conrad Paulson, Wiss, Janney, Elstner Associates	ACI Foundation, CPF, CRSI	2014
Setting Bar-Bending Requirements for High-Strength Steel Bars	Wassim M. Ghannoum, The University of Texas at San Antonio	ACI Foundation, CPF, CRSI Education and Research Foundation	2015
Defining Structurally Acceptable Properties of High-Strength Steel Bars through Beam Testing and Archetype Building Benchmark Analyses	Jack Moehle, University of California, Berkeley	ACI Foundation, CPF	2016
Defining Structurally Acceptable Properties of High-Strength Steel Bars through Material and Column Testing	Wassim M. Ghannoum, The University of Texas at San Antonio	ACI Foundation, CPF, various material suppliers	2016
High-Strength Steel Bars in Reinforced Walls: Influence of Mechanical Properties of Steel on Deformation Capacity	Andrés Lepage, University of Kansas	ACI Foundation, CPF, CRSI Education and Research Foundation	2018
Acceptable Elongations and Low-Cycle Fatigue Performance for High-Strength Reinforcing Bars	Wassim M. Ghannoum, The University of Texas at San Antonio	ACI Foundation, CPF, CRSI Education and Research Foundation	2019
Low-Cycle Fatigue Effects on the Seismic Performance of Concrete Frame and Wall Systems with High-Strength Reinforcing Steel	Gregory Deierlein, Stanford University	ACI Foundation, CPF, CRSI Education and Research Foundation	2019
Reinforced Concrete Coupling Beams with High-Strength Steel Bars	Andrés Lepage/Rémy Lequesne, University of Kansas	ACI Foundation, CPF, CRSI Education and Research Foundation	2020
Development and Splice Lengths for High-Strength Reinforcement	Robert Frosch/Santiago Pujol, Purdue University	ACI Foundation, CPF, CRSI Education and Research Foundation	2020
Shear Friction Capacity of Concrete Joints with High-Strength Reinforcement	Paolo Calvi, University of Washington	ACI Foundation, University of Washington	2020
Normal- and High-Strength Continuously Wound Ties	Bahram Shahrooz, University of Cincinnati	ACI Foundation, CPF, CRSI Education and Research Foundation	2022
Development of Large High-Strength Headed Reinforcing Bars	David Darwin, University of Kansas	ACI Foundation, CPF, CRSI Education and Research Foundation, BarSplice Products, Dextra, Headed Reinforcement Corp., Pentair	In progress
Foundation Mats with High-Strength Reinforcement	Jack Moehle, University of California, Berkeley	ACI Foundation, CPF, CRSI Education and Research Foundation, MKA Foundation	In progress
Design Requirements for Mechanically Spliced High-Strength Reinforcing Bars in Hinge Regions	Wassim M. Ghannoum, The University of Texas at San Antonio	ACI Foundation, CPF, CRSI Education and Research Foundation, CRSI member donations	In progress

collaboratively with a target in mind," Moehle said. "The project group then works with the ACI 318 Structural Concrete Building Code Committee to make sure it is a high-priority item for the Code cycle. This made a big difference in the 2019 Code cycle. It was remarkable how things moved forward so quickly."

Ellis expects ongoing and new research to continue informing changes for ACI 318-25. Collaboratively funded research projects in progress include studies on mechanical splices and large, high-strength headed reinforcing bars, plus an ongoing project led by Moehle on thick concrete foundation elements with HSR.

Moehle's research is taking place at the University of California, Berkeley, Berkeley, CA, USA, where he serves as a Professor of Structural Engineering in the Department of Civil and Environmental Engineering. The results may impact how foundations are placed for tall buildings, including high-rises. While the COVID-19 pandemic and resulting supply chain issues have caused some delays, Moehle's team is on track to complete work before the next Code cycle.

2019 Code Cycle Changes

Stronger reinforcing bar can transfer much higher stresses, but it also may lack the benchmark properties of weaker steels, such as minimum strain-hardening and elongation. As a result, incorporation of high-strength steel into ACI 318 required extensive Code changes:

- Table 20.2.2.4(a) permits the use of Grade 100 reinforcement to resist moments and axial forces from gravity and wind load combinations;
- Concerns about serviceability (cracking and deflections) were addressed through a series of changes for slab and

ACI 318 Code Cycle

A typical code cycle for ACI 318 is 6 years, and the code-change process is elaborate, said Jack Moehle, former Chair of ACI Committee 318. While anybody can submit a code-change proposal, most are developed by subcommittees of ACI 318. Every proposal must include the reason for the code change, the description of the change, and materials that support the change.

Simply put, voting on change proposals generally is done through a letter ballot process with a canvassing period that takes no less than 30 days. After voting is closed, all negative votes must be resolved. This is typically done by either adopting changes that are acceptable to the negative voter or convincing the voter—through sound explanations of the change proposal—to retract the negative vote. If the proposed change passes a subcommittee, it is then presented to the main committee, where the ballot voting and negative vote resolve/retract processes are repeated.

Code changes passed by the main committee are incorporated into a draft of the updated standard and sent to the Technical Activities Committee (TAC) for review of technical content and correctness, among other things. This may involve some back and forth between TAC and the committee to resolve any issues and negative votes. Next, the standard undergoes an ACI Standards Board review to ensure ACI procedures have been followed.

The final steps include a 45-day public comment stage, during which the standard with proposed changes is made available to ACI members, and announced in *Concrete International*. What follows is a period dedicated to responding to every public comment—the main committee responds and TAC reviews those responses. The last step is a 90-day public posting of the final response.

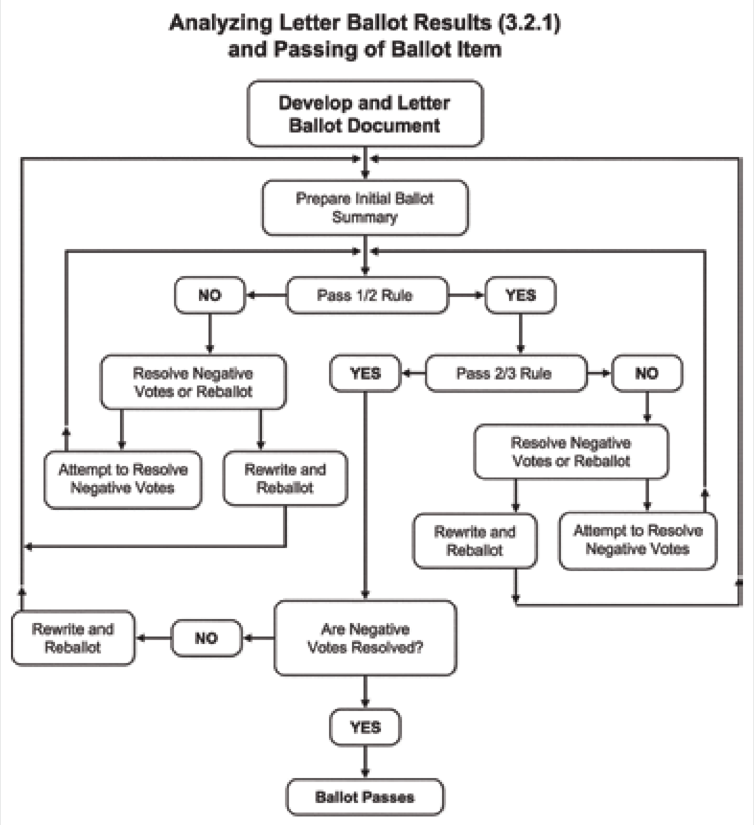

Fig. 3.2.1—Analyzing letter ballot results and passing of ballot items, 2022 ACI Technical Committee Manual. "Pass 1/2 Rule" means at least half of all eligible voting members must cast an affirmative vote. "Pass 2/3 Rule" refers to the requirement that the number of affirmative votes must be at least twice the number of negative votes

Timeline: HSR in U.S. Codes

1950s/early 1960s: Intermediate Grade (Grade 40) and Hard Grade (Grade 50) reinforcement were used in construction and codes.

1959: ASTM specifications A432, "Specification for Deformed Billet Steel Bars for Concrete Reinforcement with 60,000 psi Minimum Yield Point," and A431, "Specification for High-Strength Deformed Billet-Steel Bars for Concrete Reinforcement with 75,000 psi Minimum Yield Strength," were published, which introduced Grade 60 and Grade 75 reinforcement, respectively.

1963: ACI 318 allowed the use of steel bars with a yield strength of 60 ksi.

1968: ASTM A615, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," was introduced, which included Grades 40, 60, and 75. This became the most commonly referenced specification for reinforcing bars.

1971: ACI 318-71 increased the upper limit for yield strength to 80 ksi—but restricted the maximum specified yield strength to 60 ksi for reinforcement in special seismic systems. Some secondary reinforcement, such as confinement steel, was allowed up to 100,000 psi yield.

1974: ASTM A706, "Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement," was published. The specification for reinforcement included more restrictive tensile properties and chemistry controls.

1997: ACI 318 permitted ASTM A706.

1983: ACI 318 still required ASTM A706 for special seismic systems, but ASTM A615 was permitted if specified mechanical properties were met.

2004: ASTM A1035/A1035M, "Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement," included Grade 100.

2007: ASTM A1035/A1035M added Grade 120.

2009: ASTM A615/A615M and ASTM A706/A706M included Grade 80.

2011: ACI 318 adopted ASTM A615/A615M and A706/A706M without restriction in the main body because the use of Grade 80 reinforcement was already permitted. However, Grade 80 was not permitted for use in special moment-resisting frames and special structural walls.

2019: ACI 318-19 permits Grade 80 reinforcement for some special seismic systems and no longer allows Grade 40 reinforcing bar to be used in seismic applications. Shear walls can employ reinforcing bar in Grades 60, 80, or 100. Special moment frames can use Grades 60 or 80.

beam minimum reinforcement, effective moment of inertia, and requirements for deflection calculations for two-way slabs;

- Strength and ductility concerns were addressed by introducing new requirements for mechanical properties of reinforcing bars, adjusting the method for calculating the strength-reduction factor for moment and combined moment and axial load, revising development length provisions, and limiting the value of f_y that can be used for calculating the maximum axial compressive strength $P_{n,max}$ of columns;
- The adjustment was made to the strength-reduction factor for moment and combined moment and axial force: Compression-controlled failure for net tensile strain is defined as $\varepsilon_t \leq \varepsilon_{ty}$ and tension-controlled failure as $\varepsilon_t \geq \varepsilon_{ty} + 0.003$, where ε_{ty} is the nominal yield strain of the deformed reinforcement;
- Sections of nonprestressed beams and slabs with $P_u < 0.10 f_c' A_g$ are required to be tension-controlled so that the strength-reduction factor is always 0.9;
- ASTM A706/A706M Grade 80 reinforcement is permitted for special moment frames; ASTM A706/A706M Grade 80 and ASTM A706/A706M-equivalent Grade 100 reinforcement for special structural walls. The provisions allow the use of the higher grades to resist moments, axial forces, and shear;
- Additional restrictions on hoop spacing, beam-column joint dimensions, and lap splice locations were added to contribute to more reliable performance of special structural systems;
- Changes to provisions for standard hooks and headed deformed bars better represent the effects of bar diameter, concrete compressive strength, spacing between reinforcement, and the level of confining reinforcement on required lengths; and
- The provisions for the development of deformed bars are similar to those in past Codes, but with an additional factor $\psi_g \geq 1.0$ and a requirement for transverse reinforcement when higher grades of reinforcement are used.

ACI 318-19 was adopted by reference to the 2021 International Building Code.[5]

The Power of Collaboration

To date, the ACI Foundation, CPF, CRSI, and others have provided over $3 million in combined funding for the HSR research projects. CRSI and its member companies have contributed additional funding as well as materials, people, and knowledge. Participants in the collaborative include several ACI technical volunteers who serve on relevant committees. Among those participants is Andrew Taylor, the current Chair of ACI Committee 318.

"When you have a collective collaborating to advance the research, you can capitalize on the breadth and depth of knowledge from across the industry—which aids significantly in the code development process," Ellis said. "And when you bring a new idea forward to a technical committee, it's helpful if there are people on that committee who have weighed in during the research process. Having these diverse interests involved in our research projects helps to improve the outcomes and the impact significantly."

Plus, Ellis said: "Applied research is so much more powerful when informed by those who will use HSR. Designers, contractors, materials suppliers, and educators are all weighing in on the research program. Metallurgists and reinforcing bar manufacturers are involved, so they not only share their knowledge but also can begin to tool up for the change in the marketplace."

Moehle said CPF's blueprint—identify the problem, create a roadmap to fix it, and use research to reach the end goal—was key to the swift transitions from concept to material development to research to Code updates.

"Having it all coordinated in this manner—the roadmap, the directed funding mechanism, the advisory committees, the regular meetings, and then making sure all the stakeholders were at those meetings—kept information flowing and research progressing," he said.

With momentum established, CPF is preparing to exit the HSR research initiative to focus on another industry need: performance-based design. Ellis is hopeful that the reinforced concrete industry will see the remaining research to the end.

"There's still more to be done, and we hope others in the industry will carry forward with the necessary research as our Foundation pivots to other topics. Their contributions will broaden and deepen the understanding needed for the use of HSR products in the marketplace," Ellis said.

The HSR research initiative has been going strong for nearly 10 years, and it has helped establish best practices for future industry collaboration.

"The ACI Foundation is committed to building the future of the concrete industry through funding research and innovation," Masek said. "We are always seeking collaboration opportunities to provide needed solutions for industry needs."

References

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3. "Use of High-Strength Reinforcement in Earthquake-Resistant Concrete Structures," NIST GCR 14-917-30, National Institute of Standards and Technology, Gaithersburg, MD, Mar. 2014, 231 pp.

4. "ATC-115 Project," Charles Pankow Foundation, McLean, VA, www.pankowfoundation.org/our-work/research-grants/concrete/high-strength-rebar/03-14-development-of-tentative-specification-for-high-strength-steel-reinforcing-bar/. (last accessed Nov. 3, 2022)

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Selected for reader interest by the editors.

Special Acknowledgment

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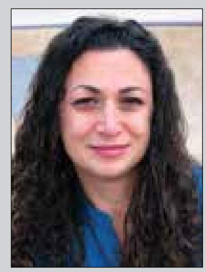

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