Precast Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC) for Fast and Sustainable Pavement Repair

Ashish Karmacharya and *Shih-Ho* Chao*

Department of Civil Engineering, the University of Texas at Arlington, Arlington, Texas 76019

Abstract. This paper presents a new methodology, which enables streets, roads, highways, bridges, and airfields to use an advanced fiber-reinforced concrete material, which can delay or prevent the deterioration of these transportation infrastructure when subjected to traffic and environmental loadings. The major problem of concrete is its considerable deterioration and limited service life due to its brittleness and limited durability. As a result, it requires frequent repair and eventual replacement, which consumes more natural resources. Ultra-high-performance fiber-reinforced concrete (UHP-FRC) introduces significant enhancement in the sustainability of concrete structures due to its dense microstructure and damage-tolerance characteristics. These characteristics can significantly reduce the amount of repair, rehabilitation, and maintenance work, thereby giving the transportation infrastructure a longer service life. This research addresses the strong need to develop fast and sustainable UHP-FRC materials for pavement repair that can be easily cast onsite without special treatments. This avoids any major changes to current concrete production practice and accelerates the use of UHP-FRC materials. This research investigated a new method for concrete repair by combining precast UHP-FRC panels with a small quantity of cast-in-place UHP-FRC for pavement repair without any dowel bars.

1 Introduction

Statistical data shows that in industrially developed countries about 40 percent of total construction costs are related to repair, replacement, and maintenance of existing structures that have deteriorated or been damaged by environmental stress, structural loading, or other effects [1]. The durability issues of infrastructure can lead to a significantly higher life-cycle cost in comparison to the initial construction cost. Fast pavement deterioration can be caused by climate change, overloaded and increasing traffic, and other environmental loads. For example, climate changes such as summer heatwaves, droughts, freezing temperatures, and flooding can have major impacts on pavement maintenance and rehabilitation costs. These extreme events are likely to occur in greater frequency and intensity in the future as the global temperature continues to rise. Interaction of temperature and precipitation patterns increase cracking [2, 3]. Consequently, pavement maintenance and rehabilitation cost could increase considerably due to both the influences of climate change and transport demand changes. Deficiencies in conventional concrete and its subsequent impact on the environment calls for a much more durable material that will last longer under environmental stress, thereby contributing to the conservation of natural resources and the protection of the ecosystem. Pavement repair or rehabilitation can broadly be categorized into three methods: 1) pavement repair using conventional concrete, 2) pavement repair using rapid setting concrete, and 3) pavement repair using precast panels. Choice of a particular method depends on the requirements of the project. It also depends on other parameters such as the available curing time, the ambient temperature, the material cost, and the desired performance. Each of the three pavement repair methods has its own advantages and disadvantages which must be considered with respect to the project requirements. The pros and cons of each method that follows refer to airfield pavement [4]; however, that type of pavement certainly qualifies as a pavement that is subject to heavy loads and high wear:

1.1 Pavement repair using conventional concrete

Conventional concrete has been in use for a very long time. As a result, contractors and workers have the tools, equipment and necessary experience required for working with conventional concrete. Compared to rapid setting concrete and precast panels, it is easier to work with this type of concrete and the materials are readily available on the market. Also, cost estimates can be done with a reasonable degree of accuracy. The cost of using conventional mix is lower than that of rapid setting concrete and precast panels. It results in a pavement with low maintenance and a longer life span compared to the other two. The major disadvantage of this pavement repair method is a longer reopening time. This mix

---

[*] Corresponding author: shchao@uta.edu

requires considerable construction as well as curing time, which leads to a very long downtime. Also, if the concrete used for the repair does not meet the determined specification, the concrete must be removed and placed again.

1.2 Pavement repair using rapid setting concrete

This type of concrete mixture is tailored to obtain very high early strength. The high early strength provides the required compressive strength within a few hours. This allows for the opening of the pavement for driving with minimum downtime. However, rapid setting concrete can have a lower final strength. Mixes for rapid setting concrete present problems such as poorly formed air voids, less homogeneous paste and increased microcracking, alkali silica reaction (ASR), and a high degree of scaling [5]. As a result, the life span is shorter than regular conventional concrete. A very low setting time of the concrete poses many difficulties such as a larger work force and precise scheduling. Also, inexperienced contractors not accustomed to working with this type of concrete make the labor arduous. The concrete has low workability and has an increased safety risk to workers because of the caustic nature of some accelerants. If the specifications are not met, the concrete must be redone which takes additional time and money.

1.3 Pavement repair using precast panels

Using precast slabs permits rapid repair of pavement. The panels are fabricated off-site in a controlled environment. This ensures good quality of concrete. The strength can further be improved by prestressing. Despite the merits, using precast panels for pavement repair poses some challenges. Inexperienced contractors and workers unfamiliar with this type of pavement repair can cause the project to get off schedule. Also, transporting the precast panels from the precast plant to the site and positioning them into place can be difficult. The edges of the precast panels are likely to get damaged and repairing them may require power grouting or lifting screw jacks. However, using precast panels provides a very fast (sometimes overnight) replacement of damaged existing pavement [6]. A prior case study for airfield pavement also showed that an 1830 m (6,000-ft) taxiway reconstruction was done by using precast panels with only overnight closures, compared with a 90-day closure for conventional methods [7].

This research offers a new methodology which enables the transportation infrastructure to use an advanced fiber-reinforced concrete material known as ultra-high-performance fiber-reinforced concrete (UHP-FRC), which can delay or prevent the deterioration of transportation infrastructure when subjected to traffic and environmental loadings. The major problem of concrete is the considerable deterioration and consequent repair work needed due to its brittleness and limited durability. The consequence of concrete deterioration and short service life requires frequent repair and eventual replacement, which consumes more natural resources. UHP-FRC is a new generation of fiber-reinforced concrete which has ultra-high ultimate and early compressive strength (> 125 MPa [18 ksi]; >70 MPa [10 ksi] after 24 hours.) and ductility. UHP-FRC was developed by changing the porous nature of conventional concrete through reducing dimensions of microcracking (or defects) in the concrete. This is achieved in UHP-FRC through a very low water to cementitious materials ratio (0.18 to 0.25) and a dense particle packing [8], which leads to almost no shrinkage or creep, making it very suitable for concrete members under long-term loading. The consequences of a very dense microstructure and low-water ratio results in enhanced compressive strength and delayed liquid ingress. Furthermore, the addition of steel or synthetic fibers works against the brittle nature of concrete by increasing the tensile cracking resistance, post-cracking strength, ductility, and energy absorption capacity. In terms of corrosion resistance, research has indicated that UHP-FRC has a much greater durability than conventional concrete due to its very dense microstructure. This dense microstructure impedes the conductive chloride ions from coming into direct contact with the steel reinforcing bars, which protects the reinforcing bars from corrosion. Table 1 provides a comparison between typical conventional concrete and UHP-FRC.

Table 1. Comparison of typical conventional concrete and UHP-FRC (all data from UT Arlington research except rapid chloride penetration test).

Properties of Concrete	Conventional Concrete	UHP-FRC
Ultimate Compressive Strength	< 8,000 psi (55 MPa)	18,000 to 30,000 psi (124 to 207 MPa)
Early (24-hour) compressive strength	< 3000 psi (21 MPa)	10,000 – 12,000 psi (69 to 83 MPa)
Flexural Strength	< 670 psi (4.6 MPa)	2,500 to 6,000 psi (17 to 41 MPa)
Shear strength	< 180 psi (1.2 MPa)	> 600 psi (4.1 MPa)
Direct Tension	< 450 psi (3 MPa)	up to 1,450 psi (10 MPa)
Rapid Chloride Penetration Test [9]	2000-4000 Coulombs passed	Negligible (< 100 Coulombs passed)
Ductility	Negligible	High ductility
Ultimate Compressive Strain, ε_{cu}	0.003	0.015 to 0.03
Confining	Negligible	High confining capability

This research addresses the strong need to develop readily available and sustainable UHP-FRC materials for pavement repair that can be easily cast onsite without special treatments such as heat, pressure, and vacuum, thereby avoiding any major changes to current concrete production practice thereby accelerating the use of UHP-

FRC materials. Taking advantage of the early strength and durability of UHP-FRC, this research investigated the viability of UHP-FRC in fast repair of pavement. This research explored using precast UHP-FRC panels for pavement repair without dowel bars.

1.4 Proposed repair method using UHP-FRC precast panels

A new method for pavement repair was proposed combining the features of precast UHP-FRC panels with a small quantity of cast-in-place UHP-FRC pavement repair without any dowel bars (Figure 1).

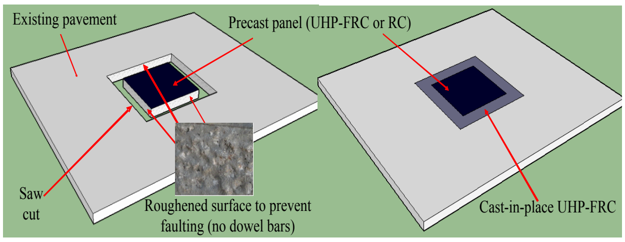


Fig. 1. Proposed method for UHP-FRC pavement repair.

This method permits the incorporation of the rapid repair feature of precast pavement panels without the inherent challenges. Also, because it uses a UHP-FRC precast panel, there is no problem of edge damage on the panels. In this method, a precast UHP-FRC panel is used along with a cast-in-place UHP-FRC. The vertical repair surfaces of the existing concrete are roughened on site. The outer edges of the UHP-FRC precast slabs are roughened before being brought to the site (no dowel bars are needed). The depth of the precast UHP-FRC is the same as the existing pavement slab thickness. Only a small cast-in-place UHP-FRC joint 25 to 50 mm (1 to 2 inches) wide is done onsite. The roughened precast UHP-FRC panel is placed in the repair area and the UHP-FRC is cast in the joint.

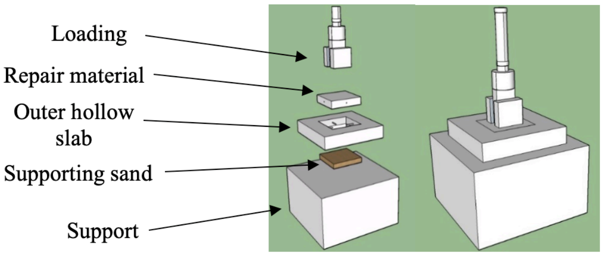
2 Experimental study

The following tasks were carried out in the experimental program:

(1) Material development for suitable pavement UHP-FRC mixtures including mixtures with steel or synthetic fibers. The procedure was similar to that used by Aghdasi et al. [8].

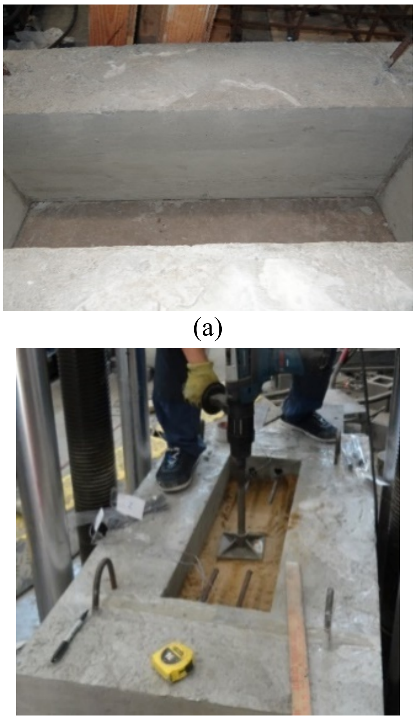
(2) This research used a punch testing to simulate the pavement interface slip and investigated the interface strength (Figure 2). It is a new test method developed in this research to simulate the actual interface strength for the proposed repair method. The early interface shear strength (24 hours) between existing concrete and repairing concrete was investigated. Two punch specimens were prepared to compare the interface shear capacity between the pavement's existing concrete and the repair concrete material. Both specimens consisted of an outer hollow slab (existing conventional concrete) with external dimensions of 1270 × 711 mm^2 (50 × 28 in.^{2}) and internal hollow section with dimensions of 762 × 254 mm^2 (30 × 10 in.^{2}) with a total depth of 254 mm (10 in.). The depth of the part being replaced (as shown in Figure 3) for both the specimens was selected as 101 mm (4 in.). For this, typical river sand was used to simulate the soil underneath concrete pavement and provided a base for the top repair slab. As shown in Figure 3, sand was poured into the hollow portion and compacted to obtain a firm support with a thickness of 153 mm (6 in.).

Figure 4a shows the dimensions and location of the dowel bars for the conventional repair method. A smooth interface surface to simulate the saw cut surface was created by using a wooden formwork (Figure 3a). Four No. 4 rebars of 432 mm (17 in.) long were used as dowel bars with a length of 216 mm (8.5 in.) embedded in the outer hollow slab and remaining in the inner cast-in-place slab as shown in Figure 4a. The rebars were positioned at a depth of 51 mm (2 in.) from the top surface (mid depth of the repair cast-in-place concrete slab). One strain gauge was mounted on each dowel bar one inch from the interface. Sand was placed in the hollow portion of the slab and compacted followed by the casting of a repair PC. Figure 5 shows the actual specimen.



(a) **(b)**

Fig. 2. Punch test setup for (a) an exploded view and (b) a normal view.



(a)

(b)

(c)

Fig. 3. (a) Interface surface between the old concrete and the repair material, (b) placing and compacting sand to obtain a uniform surface for casting, and (c) the finished sand surface at a depth of 101 mm (4 in.).

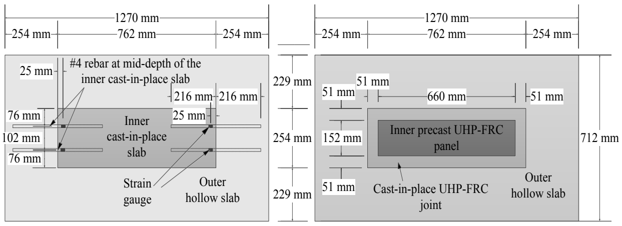


Fig. 4. Specimen details for punch test specimen (a) Specimen with No. 4 rebars and cast-in-place PC (b) Specimen with an inner precast UHP-FRC panel and a cast-in-place UHP-FRC joint.

Fig. 5. (left) Placing and compacting of sand and (right) cast-in-place PC punch test specimen.

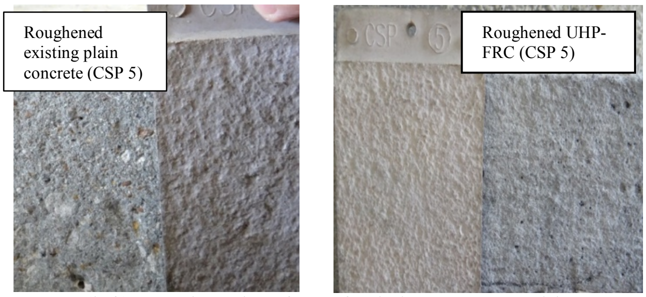


Fig. 6. (left) Roughened surface of existing concrete with a roughness level of CSP 5 and (right) roughened surface of the precast UHP-FRC panel with CSP 5.

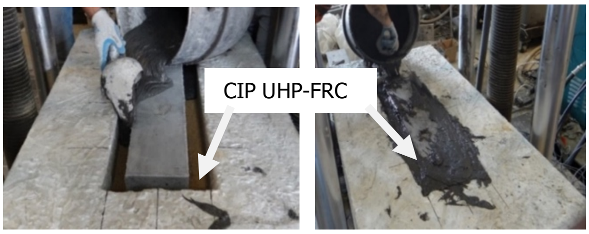


Fig. 7. Cast-in-place UHP-FRC between the precast UHP-FRC panel and existing plain concrete slab (no dowel bars were used).

The second specimen was prepared to investigate the proposed repair method shown in Figure 1. As shown in Figure 4b, a precast UHP-FRC panel with dimensions of 660 × 152 × 102 mm^3 (26 × 6 × 4 in.^{3}) was prepared. The outside surfaces of the precast UHP-FRC panel along with the inner walls of the outer hollow slab up to a depth of 102 mm (4 in.) was roughened to a roughness level of CSP 5 (Figure 6). CSPs are a set of surface roughness defined by the International Concrete Repair Institute (ICRI). It is numbered from CSP1 to CSP9 in which the surface CSP9 has the maximum roughness. Sand was filled in the hollow portion of the slab and compacted to obtain a firm support. The UHP-FRC precast panel was then placed in the middle of the repair area, and the remaining area was filled with cast-in-place UHP-FRC (Figure 7). The specimen was then cured at an average temperature of 37.8 °C (100 °F) for 24 hours using heating lamps. The primary purpose of using the UHP-FRC precast panel is to significantly reduce the required volume of UHP-FRC to be cast on site. This would simplify the repair work and maintain a high-quality pavement as well as further aid in reducing the curing time of the cast-in-place UHP-FRC.

3 Experimental results

Among the different mixes that were tried during this phase, the UHP-FRC consisting of 0.75% polyethylene fibers per unit volume of concrete was chosen. The mix was cured at a temperature of 65 °C (150 °F) and gained a one-day compressive strength of 67.8 MPa (9.84 ksi). However, in the UHP-FRC punch test specimen, the heating setup was able to maintain an average temperature of 38 °C (100 °F). This resulted in a one-day compressive strength of 47.6 MPa (6.9 ksi). Table 3 summarizes the results of the punch tests. The No. 4 dowel bars showed negligible strain when the peak vertical load was reached (Figure 8). This implies that the dowel bars had no contribution to the interface bond strength unless significant interface slip was reached. The strain in the rebar increased significantly after the interface strength of concrete started to degrade. This study shows that it is possible to use a roughened surface without a post-installed dowel bar to reduce the labor and repair time. The roughened surface could be created by a jack hammer or other tools. The UHP-FRC punch test specimen consisting of precast UHP-FRC panel and a cast-in-place UHP-FRC joint showed 30% greater peak vertical load than that of the cast-in-place PC specimen with dowel bars. The PC specimen has a shear strength of about 120 psi while the UHP-FRC specimen with the roughened surface had a shear strength of about 160 psi. The PC punch test specimen exhibited a rapid strength drop (Figure 8) after reaching the peak load while the UHP-FRC specimen maintained the peak vertical load up to a significant vertical deformation followed by a gradual decrease in the load (Figure 8). This ductility allows force redistribution in the actual pavement should the load exceed the capacity of the UHP-FRC strip used for repair.

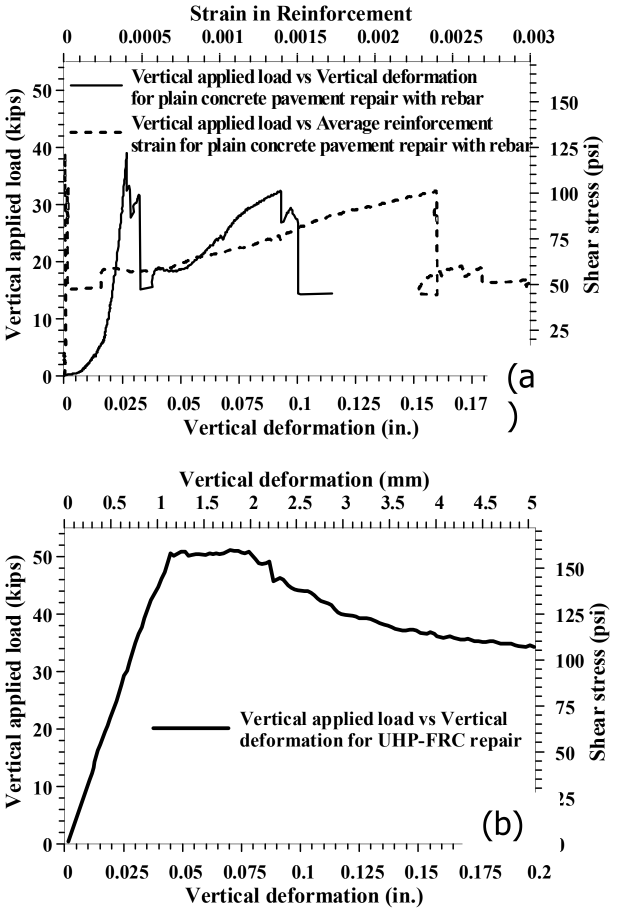


Fig. 8. (a) Vertical applied load vs. strain in reinforcement and vertical deformation for plain concrete specimen (with dowel bars) and (b) vertical applied load vs. vertical deformation for UHP-FRC specimen (1 kip = 4.44 kN, 1 psi = 6.89 kPa, 1 in = 25.4 mm).

Table 2. Results for punch test specimens.

Punch specimen	**Peak applied vertical load, kN (kips)**	**Vertical deformation at peak, mm (in.)**	**Shear stress, kPa (psi)**
PC with dowel bars and interface surface smooth	173 (39)	0.76 (0.03)	848 (123)
UHP-FRC without dowel bars and interface roughness CSP 5	227 (51)	1.02 (0.04)	1103 (160)

4 Summary and conclusions

1. Conventional concrete pavement repair uses saw cutting to remove the damaged portion and leaves a smooth surface at the cut surface. It then uses dowel bars to engage the new and existing concrete pavement to transfer the force and prevent faulting between the interface; however, experimental tests from this study showed that the rebars used as dowel bars to prevent faulting do not play a major role in the interface load transfer at the peak load. A certain vertical deformation of the pavement (i.e., damage or faulting) is required before the dowel bars can start carrying the load. From this observation, it can be concluded that the replacement of dowel bars by a roughened interface is feasible. This research showed that using a roughened surface (up to about CSP 5) provides a very large bond resistance, which is enough to prevent faulting. Replacing dowel bars by roughening the surface can eliminate the preparation time for dowel bars (drilling holes and waiting for epoxy to harden). While drilling holes might take less time than that for roughening the surface, the curing time for epoxy can take several hours.
2. A new method for concrete repair was developed, which combines the features of precast UHP-FRC panels with cast-in-place repair of pavement without any dowel bars (Figure 1). In this method, a precast UHP-FRC panel is used along with cast-in-place UHP-FRC. The vertical repair surfaces of the existing concrete are roughened on site. The outer edges of the UHP-FRC precast slabs are roughened before they are brought to the site (no dowel bars are needed). The depth of the precast UHP-FRC is the same as the existing pavement slab thickness. Only a small cast-in-place UHP-FRC joint (25 to 50 mm [1 to 2 inches] wide) is done onsite. The roughened precast UHP-FRC panel is placed in the repair area and UHP-FRC is cast into the joint.
3. This proposed method has several advantages over the conventional repair methods: (1) Pavement reconstruction using precast panels needs only overnight closures, compared with a long-term closure for conventional methods [7]; (2) the largest portion of the repair is precast, which provides higher quality control than cast-in-place concrete; (3) a limited amount of cast-in-place UHP-FRC is used and dowel bars are eliminated, which reduces the work and labor, as well as the downtime; 4) UHP-FRC can gain high early strength in a few hours, which can accelerate the repair work, and 5) UHP-FRC has great durability which allows a reduced life-cycle cost compared with the other repair methods.

References

1. Mehta, P.K., and Monteiro, P.J.M., Concrete—Microstructure, Properties, and Materials, Fourth Edition, McGraw-Hill, 2014.

2. Federal Highway Administration. (2015), Climate Change Adaptation for Pavements, TechBrief, FHWA-HIF-15-015, 12 pp.
3. Mallick, R.B., Jacobs, J.M., Miller, B.J., Daniel, J.S., and Kirshen, P. (2016). Understanding the impact of climate change on pavements with CMIP5, system dynamics and simulation. International Journal of Pavement Engineering, DOI: 10.1080/10298436.2016.1199880.
4. Federal Aviation Administration, U.S. Department of Transportation, September 28, 2007, Rapid Construction of Rigid (Portland Cement Concrete) Airfield Pavements, Advisory circular No: 150/5370-16.
5. Van Dam, T.J., Peterson, K.R., Sutter, L.L., Panguluri, A., Sytsma, J., Buch, N., Kowli, R., and Desaraju, P. (2005). Early-Opening-to-Traffic Portland Cement Concrete for Pavement Rehabilitation. NCHRP Web Document 76. National Cooperative Highway Research Program, Washington, DC, 2005.
6. Gillen, S., Gancarz, D.J., and Tayabji, S. (2018). Precast Concrete Panels for Rapid Full-Depth Repair of CRCP – Maintaining continuity of longitudinal reinforcement. Concrete International, October 2018, 39-44.
7. Switzer, W.J., Fischer, A., Fuselier, G.K., Smith, P.J., and Verfuss, W. (2003). Overnight Pavement Replacement Using Precast Panels and Conventional Subgrade Material, Washington Dulles International Airport Case Study. Airfield Pavement Specialty Conference (ASCE), 259 – 278, 2003.
8. Aghdasi, P., Heid, A.E., and Chao, S.-H. (2016). Developing Ultra-High-Performance Fiber-Reinforced Concrete for Large-Scale Structural Applications. ACI Materials Journal, **113**(5), September-October 2016, 559-570.
9. Ahlborn, T., Harris, D., Misson, D., and Peuse, E. (2011). Characterization of Strength and Durability of Ultra-High-Performance Concrete Under Variable Curing Conditions. Journal of the Transportation Research Board, No. 2251, 68–75.