Compressive Strength and Tensile Characteristics of UHPC with Varying Fiber Volume Fractions

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Abstract

Ultra-high-performance concrete (UHPC), with its superior mechanical characteristics and durability properties, provides opportunities to build sustainable highway infrastructure. To attain desirable properties, the presence of fibers plays an integral part in ultra-high-performance concrete (UHPC) mixes. This paper studies the influence of fiber volume on both the compressive strength and tensile behavior of UHPC. To investigate these fiber dependencies, specimens were cast using UHPC from three suppliers with three fiber volume fractions, i.e., 1%, 2%, and 3%. Cubes of 2 in x 2 in x 2 in. and cylinders with dimensions 3 in. (diameter) x 6 in. (length) were tested for compression strength comparisons at different ages according to ASTM C109/C109M-20b and ASTM C1856/C1856M-17, respectively. At 3% fiber volume, the strength ratio of cylinders to cubes was around 1. However, the strengths of cylinders were higher than cube strengths at lower fiber volumes. The strength ratio remained similar and did not vary with the age of UHPC. AASHTO T397 test procedure was used to quantify the direct tension behavior of UHPC. In addition, longer dog-bone specimens than specified in AASHTO T397 were cast to investigate the effects of change in gauge length on tensile behavior. Varying fiber volume fractions significantly influenced the tensile strength and post-cracking tensile response of UHPC. A higher volume of fibers resulted in higher tensile strength and a more extensive multi-cracking phase. The crack straining phase was dependent on the UHPC type and did not depend on fiber volume. An increase in gauge length indicated reduced residual tensile load-carrying capacities beyond localizations.

Keywords: Compressive strength, Direct tensile test, Fiber Volume, Multi-cracking, Steel Fibers, Strain Hardening, Tensile response, Ultra-high-performance concrete, cubes, cylinders.

1. Introduction

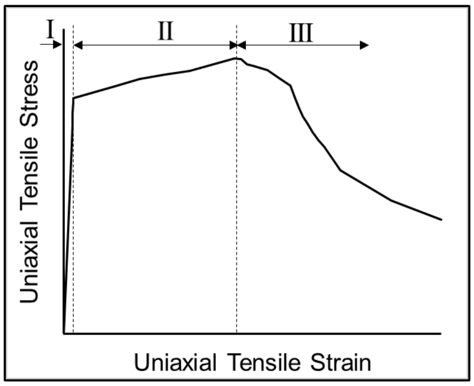
Ultra-high-performance concrete (UHPC) is high-strength, durable concrete available in the present market. Its superior mechanical properties include higher compressive strength, higher tensile strength, substantial tensile ductility, etc. when compared to conventional concrete (Sritharan et al. 2003; Graybeal 2006;). The presence of fibers provides tensile ductility and improved fracture energy (Brandt 2008; Wille et al. 2011; Gali et al. 2017). Structural applications of UHPC include precast girders, prestressed girders, precast waffle bridge deck panels, and field-cast connections. Despite several advancements in the research and development of UHPC, it is not extensively used in structural applications due to the lack of code provisions and design manuals.

Compressive strength is one of the important properties of UHPC that can be tested in the laboratory. Cylinders and cubes are standard specimen shapes used worldwide to determine the compressive strength of concrete used in structural members, which has been extended to evaluate the UHPC compression strength. Cubes and cylinders of various sizes made of normal-strength concrete, high-strength concrete, and UHPC were tested by Phillip et al. (2017). Based on the test results, it was reported that compressive strength ratios of cylinders to cubes made of UHPC are closer to 1 compared to normal strength and high-strength concretes. Graybeal and Davis (2008) extensively tested cubes and cylinders of varying sizes with 2% fiber volume. The strength ratios of cubes and cylinders were reported to be varying between 0.92 and 1.10. The use of a cylinder as a standard shape for UHPC requires a high-capacity compression testing machine and end grinding machine, limiting the number of laboratories that can perform this test. The use of cubes provides a better alternative for testing of UHPC as they have clear definitive end faces, needing no surface grinding. The presence of fibers tends to influence the compressive strength of UHPC. The factors for the conversion of cube strength to cylinder strength with varying fiber volumes have not been extensively studied.

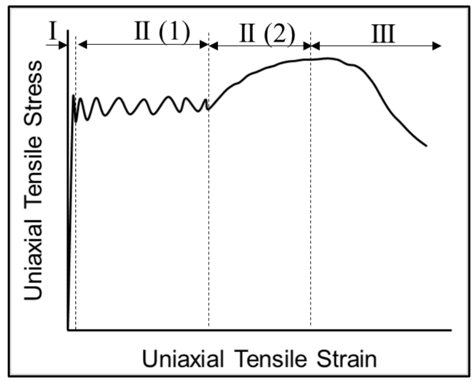
The presence of fibers in UHPC also provides higher tensile strength and post-cracking tensile resistance. The direct tensile test is proved to be a more accurate but difficult test to perform to determine the tensile behavior of concrete. Several specimen shapes and varying boundary conditions are available for direct tensile testing of conventional fiber-reinforced concrete and are being adopted for UHPC (Wille et al. 2011; Roth et al. 2010; Zhang et al. 2000; Kamal et al. 2008; Jun and Mechtcherine 2010). The use of fixed-end gripping during testing was reported to produce an accurate post-cracking tensile response for UHPC (Jun and Mechtcherine 2010; Park et al. 2012; Graybeal and Baby 2013). The test procedure developed by FHWA (Graybeal and Baby 2013), which is being adopted as AASHTO T 397 (2022), proved to be advantageous because of the ease of specimen preparation (square prisms) and the use of fixed-end gripping. An accurate representation of post-cracking tensile response can be captured using this procedure. Varying fiber volume greatly influences the tensile behavior of conventional fiber-reinforced concrete. The studies on varying fiber volumes on the tensile behavior of UHPC are limited. Also, the characterization of tensile responses, especially after localization, will depend on the gauge length used in the testing procedure. Previously, tests were performed on dog bone specimens with varying gauge lengths (Nguyen et al. 2014; Pachalla et al. 2019). Further study on the effect of gauge length on UHPC tensile behavior is required. In this paper, the influence of fibers on the compressive strength and tensile behavior of concrete is investigated. For this effort, specimens were cast using different UHPC types and fiber volumes. Cubes and cylinders were tested for compressive strength at different ages of UHPC according to ASTM C109/C109M-20b and ASTM C1856/C1856M-17, respectively. AASHTO T 397 (2022) direct tensile test procedure is used to determine the tensile behavior of UHPC. Dog-bone specimens were tested at higher gauge lengths to study the effect of gauge length on the tensile behavior of UHPC.

2. Tension Behavior of UHPC

Traditionally, tensile responses are characterized into three phases. These phases include elastic, strain hardening, and crack-based softening phases. The elastic phase is the linear material behavior before the first crack occurs. In the strain-hardening phase, several micro-cracks form along the length of the specimen, with fibers bridging the cracks. One of these cracks widens and becomes dominant, leading to softening phase of the response. Dog-bone specimen responses can be characterized using this behavior. Based on the traditional tensile response and test results observed using the FHWA test procedure, Graybeal and Baby (2013) have proposed an idealized tensile response of UHPC specimens. In this response, the strain-hardening phase is further divided into the multi-cracking and crack-straining phases. Few fibers continue to bridge the cracks during the crack-straining phase, and the remaining fibers start to debond, leading to a dominant crack. This transition phase between the multi-cracking and crack localization phase primarily depends on fiber-matrix interface bonding. The crack localization phase corresponds to the continuous debonding of fibers leading to crack widening and, thus, softening. Traditionally characterized tensile response and FHWA idealized tensile response are shown in Figure 7.



(a)



(b)

Figure 7: Characterized tensile responses of (a) dog-bone specimens and (b) FHWA tensile specimens (I-Elastic phase; II-Strain hardening phase; II (1)-Multi-cracking phase, II (2)-Crack straining phase; III- Crack based softening or crack localization phase)

2. Experimental Program

All test specimens were cast using different UHPC types with different fiber volume fractions in this test program. Three UHPC types commercially available in the United States were used in this study and were identified as UHPC1, UHPC2, and UHPC3. Three fiber volumes as a percentage of the volume of UHPC equal to 1%, 2%, and 3% were used to cast specimens with UHPC1, UHPC2, and UHPC3, respectively. Straight steel fibers with dimensions of 0.008-in. (0.2 mm) diameter and a nominal length of 0.5 in. (12.7 mm) were used in this study. Fibers have a tensile strength of 400 ksi (2758 MPa) and a modulus of elasticity of 29.8 ksi (205.5 MPa). All the UHPCs were mixed as per the instructions provided by the respective suppliers. From each mixture of UHPC, ten prismatic (square) tensile specimens of dimensions 17-inch (431.8 mm) length x 2-in. (50.8 mm) width x 2-in. (50.8 mm) depth, 2-in. (50.8 mm) cubes, and 3-in. (76.2 mm) diameter x 6-in. (152.4 mm) length cylinders were cast. In addition, two dog-bone specimens of length 36 in. (914.4 mm) with a cross-section of 2 in. (50.8 mm) x 2 in. (50.8 mm) at the center were cast separately using a UHPC1 mix design with two fiber volume fractions of 1% and 2%. Dog-bone specimens with 1% and 2% fiber volumes were identified as UHPC1_D1 and UHPC1_D2, respectively. These specimens had a 10 in. (254 mm) long prismatic (square) portion with a 2 in. (50.8 mm) x 2 in. (50.8 mm) cross-section at the center and 6 in. (152.4 mm) wide end zones to avoid failures closer to the supports. Prismatic (square) and dog-bone tensile specimens were tested to determine the tensile characteristics of UHPC. For compressive strength, three cubes and three cylinders were tested at 14 and 28 days from all three UHPCs. Cubes and cylinders were tested in compression according to ASTM C109/C109M-20b (2020) and ASTM C1856/C1856M-17 (2017), respectively.

The full test setup of the tensile test is shown in Figure 2 (b). Ten specimens were tested using the AASHTO T 397 (2022) direct tensile test procedure in this test program. Dog-bone specimens were cast with two threaded bars at each end, which were anchored to T-shaped steel plates. These plates were gripped onto the test machine, and an LVDT was attached to one face of the specimen to measure the deformations at a gauge length of 14 inches. These specimens were tested at a displacement rate of 0.02 in/min (0.42 mm/s). The full test setup with LVDT is shown in Figure 2 (c). All the test specimens were tested on a servo-controlled hydraulic test machine.

(a) **(b)** **(c)**

Figure 2: (a) Finished prismatic tension specimen with attached aluminum plates; (b) AASHTO T 397 (2022) and (c) dog-bone specimen tension test setup

3. Experimental Results

3.1. Compression Test Results

Average compression test results from three cubes and three cylinders tested at 14 and 28 days for all three UHPCs are reported in Table 1. Failure in all the specimens due to compression was by minor spalling and cracking of UHPC. At least 80% of the maximum strength was attained within 14 days of casting in all the mixes. After 28 days, the increase in strength was not substantial compared to the early-age strength increase.

Table 1: Average Compressive Strengths

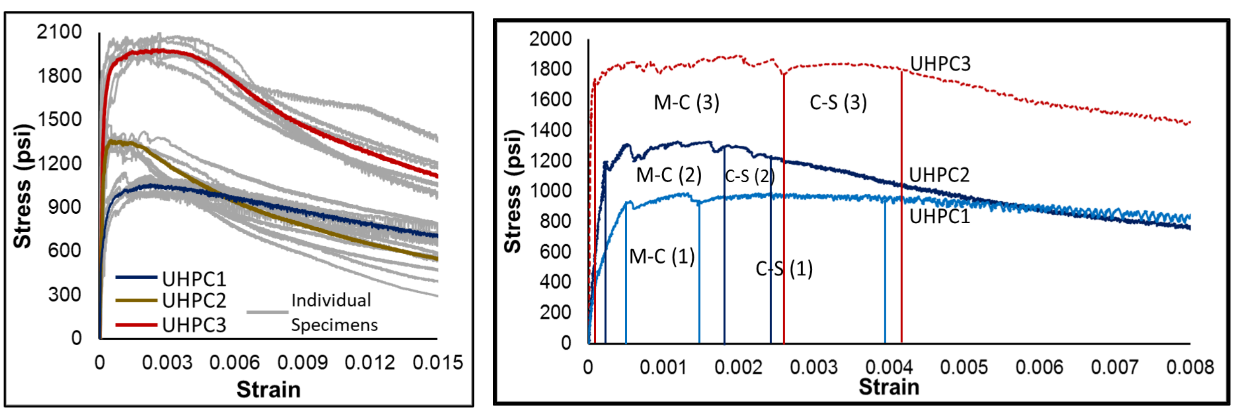
UHPC Type	**Age**	**Cylinder Mean ksi, std. dev (MPa)**	**Cube Mean ksi, std. dev (MPa)**	**Conversion factor**
UHPC1	14 days	18.1, 0.7 (124.9, 5)	16.4, 0.8 (113.1, 5.5)	1.11
	28 days	19.9, 0.5 (137.2, 3.4)	17.6, 0.5 (121.3, 3.4)	1.13
UHPC2	14 days	17.7, 0.9 (122, 6.2)	17.6, 0.7 (121.3, 4.8)	1.01
	28 days	18.7, 0.5 (128.9, 3.4)	18, 0.5 (124.1, 3.4)	1.03
UHPC3	14 days	17.8, 0.7 (122.7, 4.8)	17.4, 0.7 (120, 4.8)	1.02
	28 days	19.2, 0.8 (132.4, 5.5)	19.3, 0.78 (133.1, 5.4)	0.99

Despite using different UHPCs, the influence of fiber volume on compressive strengths is not significant. However, the relation between cube and cylinder compressive strengths varied with a change in fiber volume. Compressive strengths obtained from cubes were comparable to cylinders for UHPC3 mixes. In contrast, compressive strengths from cylinders were higher for specimens with lower fiber volumes, i.e., UHPC1 and UHPC2. This trend was consistently observed at different ages of testing. Conversion factors to obtain 3-in cylinder strengths from 2-in cube strengths vary with fiber volume. The conversion factor reported by Graybeal (2015) for UHPC with 2% fiber volume is 0.98, which is marginally lower than that found for UHPC2 and UHPC3. The conversion factors found for UHPC 1 are significantly higher. The change in conversion factors is attributed to the use of different UHPCs. The packing density of concrete varies with UHPC types, potentially leading to higher variation in strengths in smaller volume cubes than cylinders.

3.2. Tension Test Results

3.2.1. AASHTO T 397 test response

Direct tension tests were performed on specimens with 1%, 2%, and 3% fiber volume fractions. AASHTO T 397 (2022) direct tensile testing procedure was generally used to determine the tensile characteristics of UHPC1, UHPC2, and UHPC3 specimens. The average LVDT data obtained from extensometers were used to measure the deformations in the specimens. Though there were variations in responses between the specimens, typical tensile responses were captured for all fiber volume fractions. Tensile test results of specimens with crack localization within the gauge lines were used for further analyses. Tests in which specimens failed with crack localizing outside the gauge region were considered unsuccessful. These unsuccessful tests are expected when performing direct tensile tests as certain eccentricities can't be avoided during testing, causing non-uniform transfer of stresses towards the center of the specimen where failure is anticipated. Tensile responses of specimens with crack localization within the gauge lines are shown in Figure 3a.



(a) **(b)**

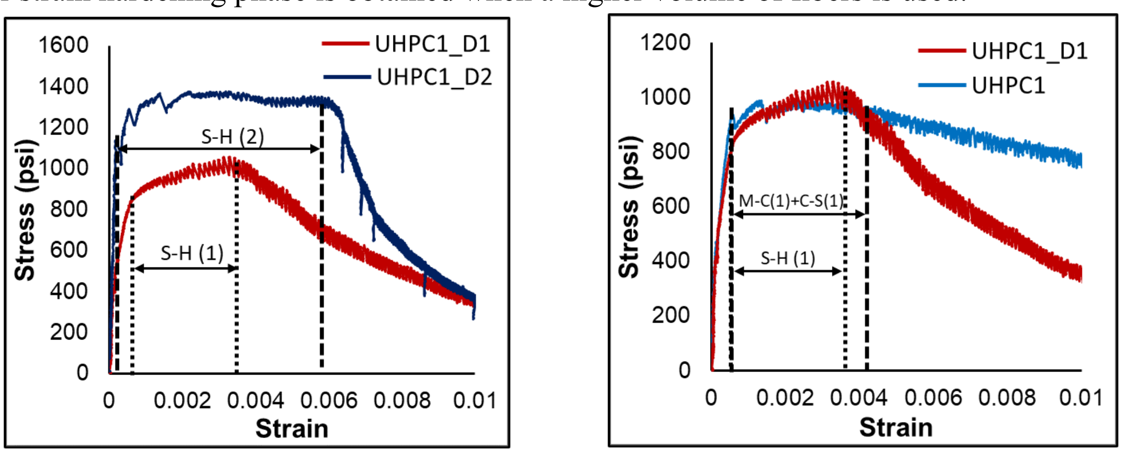
Figure 3: (a) Average tensile responses of the specimens; (b) Characterized tensile responses of one specimen from each set. (1 MPa=145 psi)

Characterized tensile responses of one specimen from each set (i.e., UHPC1, UHPC2, and UHPC3) are shown in Figure 3b. Multi-cracking phases of UHPC1, UHPC2, and UHPC3 are represented as M-C (1), M-C (2), and M-C (3), respectively. Crack straining phases of UHPC1, UHPC2, and UHPC3 are represented as C-S (1), C-S (2), and C-S (3), respectively. The extent of

M-C and C-S phases from all the specimens was obtained using the difference between the end strain values of each phase. An increase in the multi-cracking phase with fiber volume was observed due to a larger number of fibers at the crack locations. The average C-S strain varied in all three sets of specimens. This phase of the response is influenced by a combination of fiber bridging and fiber debonding. Therefore, the extent of this phase depends mainly on the fiber-UHPC matrix interface bond. Specimens with 1% fiber volume consistently showed a larger crack-straining phase than those with 2% fiber volume. From this observation, it can be stated that the crack-straining phase depends on the UHPC type rather than the fiber volume. This phase is followed by the final crack localization phase, during which fibers continuously debond, resulting in softening behavior of the tensile response.

3.2.2. Dog-bone specimen response

Dog-bone specimens UHPC1_D1 and UHPC_D2 with fiber volumes of 1% and 2% were tested. Two specimens were tested to investigate the effect of fiber volume on tensile responses with the same UHPC type. LVDT data was used to measure the deformations over a gauge length of 14 inches instead of 4 in. used for prismatic samples. In this test procedure, gripping was not directly on the specimen compared to the AASHTO T 397 (2022) test procedure. The tensile responses of the specimens are shown in Figure 4a. An increase in tensile strength with an increase in fiber volume is observed in these specimens. An increase in the number of cracks with the increase in fiber volume was observed in the specimens. Strain hardening phases of the tensile responses are represented as S-H (1) and S-H (2) for UHPC1_D1 and UHPC_D2 specimens, respectively. A larger strain hardening phase is obtained when a higher volume of fibers is used.



(a) (b)

Figure 4: (a) Tensile response of dog-bone specimens; (b) Comparison of tensile stress-strain responses of UHPC1_D1 and UHPC1 (1 MPa=145 psi)

3.2.3 Effect of gauge length

In this test program, two gauge lengths were considered for the direct tensile tests. To investigate the effect of gauge length on the tensile behavior of UHPC, specimens with the same UHPC type and the same fiber volume were used, i.e., UHPC1_1 (specimen from UHPC1 set) and UHPC1_D1 specimen. Tensile responses of these specimens, along with identifications of the strain hardening phases, are shown in Figure 4b. The strain hardening part of the UHPC1_1 tensile response was taken as a combined strain value obtained from the multi-cracking and crack-straining phases.

Tensile strengths, the differential strain of the strain hardening phase, and stress at a strain of 0.01 are shown in Table 2. Though specimens show comparable tensile strengths and strain hardening phases, change in gauge length significantly affects the tensile softening response as expected. Consequently, it follows that UHPC tension responses with a constant gauge length may not be appropriate for designing structural members with appropriate deformation quantities. This is further investigated in an ongoing study at Iowa State University.

Table 2: Tensile strength characteristics of UHPC specimens

Specimen ID	Fiber Volume, %	Tensile strength, psi (MPa)	S-H	Stress @ 0.01 strain, psi (MPa)
UHPC1	1	1061.8 (7.3)	0.00313	845.9 (5.8)
UHPC1_D1	1	1057.9 (7.3)	0.00279	383.3 (2.6)

5. Summary and Findings

Cubes and cylinders of UHPCs with different fiber volumes were tested at 14 and 28 days from casting to study the effect of fiber volume on the compressive strengths of UHPCs. All the UHPC types showed an early increase in compressive strength, with around 85% of strength attained within 14 days of casting. After 14 days, an increase in strength with age was minimal, regardless of the fiber volumes. Based on the test results, the conversion factor for cube compressive strength to obtain cylinder compressive strengths were examined. Conversion factors varied with fiber volume and were also influenced by the UHPC type. The packing density of the UHPC type is believed to have more influence on the strengths of lower-volume cubes than cylinders.

AASHTO T 397 (2022) direct tensile test procedure was used to determine the tensile behavior of UHPC. Tensile responses obtained from direct tensile testing of UHPC specimens with varying fiber volumes were characterized for different phases. An increase in tensile strength with an increase in fiber volume was consistently observed. A larger multi-cracking phase at a higher volume fraction was also noted. This can be attributed to more fibers at the crack locations allowing more cracks to develop, delaying the widening of the localized crack. Dog-bone shaped specimens were tested at a larger gauge length of 14 inches. Test results were used to study the effect of gauge length on tensile behavior. An increase in gauge length resulted in reduced residual load-carrying capacities at a given post-softening strain.

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References

- ASTM C109/C109M-20b. "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Or [50-mm] Cube Specimens)." American Society for Testing and Materials International, Philadelphia, (2020).
- ASTM C1856/C1856M-17. "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete." American Society for Testing and Materials International, Philadelphia, (2017).

- AASHTO T 397, "Standard Method of Test for Uniaxial Tensile Response of Ultra-High Performance Concrete," American Association of State Highway Transportation Officials, Washington, DC, (2022).
- Brandt, Andrzej M. "Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering." *Composite structures* 86.1-3 (2008): 3-9.
- Dobrusky, Svatopluk, and Sebastien Bernardi. "Uni-axial tensile tests for uhpfrc." *AFGC-ACI-fib-RILEM International Conference on UltraHigh Performance Fibre-Reinforced Concrete (UHPFRC 2017), RILEM Proceedings Pro*. Vol. 106. 2017.
- Gali, Sahith, and Kolluru VL Subramaniam. "Evaluation of crack propagation and post-cracking hinge-type behavior in the flexural response of steel fiber reinforced concrete." *International Journal of Concrete Structures and Materials* 11 (2017): 365-375.
- Graybeal, Benjamin A. "Practical means for determination of the tensile behavior of ultra-high performance concrete." *Journal of ASTM International* 3.8 (2006): 1-9.
- Graybeal, Benjamin, and Marshall Davis. "Cylinder or cube: strength testing of 80 to 200 MPa (11.6 to 29 ksi) ultra-high-performance fiber-reinforced concrete." *ACI Materials Journal* 105.6 (2008): 603.
- Graybeal, Benjamin A., and Florent Baby. "Development of direct tension test method for ultra-high-performance fiber-reinforced concrete." *ACI Materials Journal* 110.2 (2013): 177.
- Graybeal, Benjamin A. "Compression testing of ultra-high-performance concrete." *Advances in Civil Engineering Materials* 4.2 (2015), 4(2):102-112.
- Jun, Petr, and Viktor Mechtcherine. "Behaviour of strain-hardening cement-based composites (SHCC) under monotonic and cyclic tensile loading: part 1–experimental investigations." *Cement and Concrete Composites* 32.10 (2010): 801-809.
- Nguyen, Duy Liem, et al. "Size and geometry dependent tensile behavior of ultra-high-performance fiber-reinforced concrete." *Composites Part B: Engineering* 58 (2014): 279-292.
- Pachalla, Sameer KS, Christopher Levandowski, and Sri Sritharan. "Effects of Size and Gauge length on the Stress-Strain Response of UHPC in Tension." *International Interactive Symposium on Ultra-High Performance Concrete*. Vol. 2. No. 1. Iowa State University Digital Press, 2019.
- Park, Seung Hun, et al. "Tensile behavior of ultra-high performance hybrid fiber reinforced concrete." *Cement and Concrete Composites* 34.2 (2012): 172-184.
- Riedel, Philipp, and Torsten Leutbecher. "Effect of specimen size on the compressive strength of ultra-high performance concrete." *Proceedings of the AFGC-ACI-fib-RILEM Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete, UHPFRC*. 2017.
- Roth, M. J., et al. "Ultra-High-Strength, Glass Fiber-Reinforced Concrete: Mechanical Behavior and Numerical Modeling." *ACI Materials Journal* 107.2 (2010).
- Sritharan, Sri, B. Bristow, and V. Perry. "Characterizing an ultra-high performance material for bridge applications under extreme loads." *Proceedings of the 3rd International Symposium on High Performance Concrete, Orlando, FL*. 2003.
- Wille, Kay, Dong Joo Kim, and Antoine E. Naaman. "Strain-hardening UHP-FRC with low fiber contents." *Materials and structures* 44 (2011): 583-598.
- Zhang, Jun, Henrik Stang, and Victor C. Li. "Experimental study on crack bridging in FRC under uniaxial fatigue tension." *Journal of Materials in Civil Engineering* 12.1 (2000): 66-73.