Uniaxial Compression Behavior of Ultra-High Performance Concrete Confined by Steel Spirals

Author(s) & Affiliation: Negar Naeimi (1), Mohamed Moustafa (1)

[1] University of Nevada, Reno, NV, USA

Abstract:

The superior physical and mechanical behavior of Ultra-High Performance Concrete (UHPC) has attracted lots of interest for large number of applications such as joints and connections. However, there is still a great potential for application of UHPC in large-scale structural elements such as bridge columns. To achieve this goal, design guidelines must be developed which will require a comprehensive knowledge of the confined and unconfined UHPC material behavior. To date, no extensive studies investigated the confining effects of steel spirals on UHPC. This study addresses this gap with a focus on the compressive stress-strain behavior of UHPC cylinders confined using steel spirals. The effect of different volumetric ratios of spirals was investigated and uniaxial compression tests were carried out on the cylinders with 3 in (76 mm) diameter and 6 in (152 mm) height. UHPC cylinders were cast from one batch, used 2% steel fibers ratio, and confined with three different spiral configurations that has 1 in (25 mm), 0.5 in (13 mm), and 0.25 in (6mm) pitch and corresponds 1.9%, 3.8%, and 7.6% volumetric ratio, respectively. The overall behavior of confined UHPC cylinders from each group was compared with the reference unconfined UHPC cylinders. Moreover, the out-of-planeness of the tested cylinders along with the actual specimens' height were reported and related to the compression strength for any trending effects.

Keywords: Compression tests, confinement, steel spirals, uniaxial material response

1. Introduction

Ultra-High Performance Concrete (UHPC) is an innovative cementitious material with exceptional high strength, performance and durability. There is not a unique definition for UHPC but according to the Federal Highway Administration (FHWA), UHPC has superior mechanical and durability properties, e.g. the compression strength of UHPC is greater than 21.7 ksi [1, 2]. The high compression strength and durability associated with the low permeability of UHPC is owed to the finely mixed aggregates and cementitious materials following the particle packing theory. UHPC is a combination of Portland cement, silica fume, fine sand, ground quartz, high-range water reducer (superplasticizer), less than 0.25 water-to-cement (W/C) ratio, and fibers (usually steel fibers). Finely ground sands, nano-materials and fillers reduce the pores, and make UHPC a highly homogeneous material with low permeability. Steel fibers are dimensionally the largest constituent in UHPC whereas they play a crucial role on the ductility characteristics of the material. Steel fibers make UHPC a highly ductile material compared to High Strength Concrete (HSC).

Recently, UHPC has been used in some structures such as building components, connections and facades, bridge decks and joints, and marine structures. It is also used for the repair and rehabilitation of damaged structures. Numerical modeling and design of such structures are mostly done using existing constitutive models for conventional concrete, or at best, with some slight modifications. However, there is still lack of implemented and widely-used constitutive models for the numerical modeling and design of UHPC components and structures. In this regard, experimental tests to evaluate the UHPC material in tension and compression are essential and continue to grow. Few researches were conducted to study the uniaxial tensile behavior of UHPC such as the comprehensive work at the FHWA [3, 4]. Nonetheless, the entire stress-strain relationship including the post-peak behavior of UHPC in compression is less considered. To capture the post-peak behavior, there are several testing barriers must be tackled, and high capacity and accurate testing machines must be available with robust closed-loop control. Meanwhile, one knowledge gap that yet to be filled is understanding the behavior of confined UHPC and in turn, develop or verify the proper confinement constitutive model. Such a comprehensive material model that accounts for UHPC confinement can be employed in finite element modeling and simulations when components endure severe seismic loading. Steel spirals are commonly used in circular columns and is known to be popular for confining concrete. In this regard, this study aims at filling the aforementioned knowledge gap by looking into the confinement behavior of UHCP cylinders under various confining spirals configurations. This paper presents the results of uniaxial compression tests carried out on the different UHPC cylinders confined by steel spirals and compare it to the unconfined behavior.

2. Background

In the recent years, only a handful of published literature addressed compression stress-strain relationships of UHPC cylinders. Hassan et. al. [5] investigated the effect of steel fibers, modulus of elasticity, stress-strain curve and post peak behavior of UHPC in tension and compression. They obtained the complete compressive stress-strain curve for unconfined specimens using closed-loop controlled testing from Linear Variable Displacement Transducers (LVDTs) feedback. Based on their observations, the BS 1881-121:1983 method was unable to capture the post-peak behavior of UHPC specimens in compression because the strain gauges were detached from the specimens' surface when the concrete spalls after the peak strength. Similarly, they observed that ASTM C469 is inefficient to capture the post-peak behavior of specimens because of the rotation of clamping screws of compressometers after the formation of first cracks. Thus, they recommended the use of compressometers to measure the vertical shortening of the specimen, only in the elastic zone, and LVDTs, placed parallel to the specimen, to measure the movement of machine crosshead, in the post-peak region.

Aghdasi et. al. [6] carried out compression tests on 2.8 in (71 mm) cubic specimens cast from their proposed UHPC mixture. They used a pair of LVDTs to determine the deformation for the entire compressive stress-strain curve. Shafieifar et. al. [7] performed compression tests on five 3 in (75 mm) diameter unconfined cylinders and on five, 2 and 3 in (50 mm and 75 mm) cubic specimens, made from the Ductal© UHPC. Based on their observations, Ductal© behaved elastically up to 50% of its compressive strength. They reported the unconfined compression stress-strain curves. Moreover, there are more published works on confinement effect of steel tubes or FRP wraps on the compression behavior of UHPC cylinders (e.g [8]). On the other hand, limited studies considered UHPC steel spirals confinement. Yang et. al. [9] conducted compression tests on 3 unconfined and 18 confined UHPC cylinders using steel spirals with yield stress of 60 ksi (414 MPa). Likewise, the tested UHPC material was Ductal© with 2% steel fibers cast into 4 × 8 in (102 × 203 mm) cylindrical molds. Based on their observations, stress-strain behavior of confined specimens could be categorized into three different parts. The initial linear part was following by the nonlinear inelastic hardening region, and then by the gradual load decrease or the sudden load drop after the peak strength, while the unconfined UHPC response was relatively linear up to the peak strength, following by a sudden load drop. They found steel reinforcement more efficient than FRP for confinement of UHPC, except for very large confinement ratios, where FRP is more effective. Moreover, for the same confinement ratio, steel-confined UHPC was found to have a larger ultimate strain than FRP-confined UHPC.

3. Experimental Tests

3.1. Material and mix design

In this study, the Ductal© JS1000 commercial UHPC is used. Ductal© is composed of the premix, which is a proprietary blend of cement, silica sand, silica flour and silica fume, super plasticizer, and 2% steel fibers. In Table 1, the UHPC mix by Ductal© is presented. Based on the reported data, steel fibers have 399 ksi (2750 MPa) yield stress, 0.5 in (13 mm) length, and 0.008 in (0.2 mm) diameter. For the purpose of this study, one batch of Ductal© UHPC was mixed following rigorous mixing and sampling procedures. Materials were accurately weighed and placed in a high shear mixer (Imer Mortarman 360 mixer). The premix, superplasticizer and water (or ice when needed) were initially mixed for about 15-20 min until a good consistency is reached. Next, the steel fibers were added slowly to the paste and mixed for an additional 10-15 min. As soon as mixing was completed, the casting and sampling of test specimens was completed. The UHPC was scooped into the plastic molds and was not rodded to avoid fibers segregation. The UHPC cylinders were just hit by a hammer on the side to allow the trapped air to exit. Steel spirals were already built, specifically for the purpose of this study, and put inside the plastic molds. No UHPC cover on the spirals was considered, as illustrated in Figure 1a, to assure the whole cylinder section work as confined UHPC. Cylinders were capped and stored outside to represent actual performance of UHPC in a structural scale. Note that the UHPC paste and ambient temperature were measured and controlled to be in the allowable range during the mixing and casting. Moreover, the static and dynamic flow tests were conducted to control the quality of the UHPC paste.

Table 1. UHPC mixture by Ductal© (based on number of premix bags)

	kg/m^3	lb/yd^3	Percentage by weight
Premix (kg)	2,195	3,700	87.4
Water (or ice if needed)	130	219.1	5.2
Superplasticizer (Premia 150)	30	50.6	1.2
Steel fiber (2% volume)	156	263	6.2

3.2. Test specimens

In total, 6 unconfined and 16 confined specimens were cast from one batch into the 3×6 in (76×152 mm) plastic cylindrical molds and demolded after at least 10 days of casting. Specimens were tested between 123 and 127 days after casting. Age of the specimens at the test day, volumetric ratio of steel spirals, and number of specimens for each group of specimens are summarized in Table 2. Confined cylinders were reinforced by steel spirals of three different pitch sizes: 1, 0.5, and 0.25 in (25, 13 and 6 mm). The volumetric ratio of the wires (ρ) in confined cylinders were 1.91%, 3.82% and 7.63%, respectively. Spiral wires were of low carbon steel with 70 ksi (483 MPa) tensile strength and 0.135 in (3.4 mm) diameter. To prepare the specimens for the uniaxial compression test, top end of the confined and unconfined specimens were firstly cut using a saw machine. Next, both ends were ground using a HC-2980 specimen grinding machine.

Based on the Ductal© Operating Procedures for Cylinders End-Grinding, using a concrete saw, approximately 0.41-0.47 in (10-12 mm) of top of the cylinders shall be finished end, and the ultimate length of the cylinders must be 5.9 in ± 0.04 in (150 mm ± 1 mm). Note that the cylinders' molds are typically 3 in × 6.5 in (75 mm × 165 mm) but the molds used in this study were shorter with the height approximately equal to 6 in (152 mm). Accordingly, the finished height of the specimens were less than 6 in (152 mm). Hence, the effect of specimens' height on the compressive strength is investigated as discussed in a following section. The height of the specimens were calculated as the average of four lengths measured in two perpendicular directions at the cross section. The diameter of UHPC specimens was measured at three locations along the height: top, mid-height and bottom. At each height level, the diameter was measured in two perpendicular directions. Thus, the diameter of each cylinder is the average of six measured diameter at different locations at height and cross section. The average diameter was used to calculate the cross section area of the cylinders, which was used for stress calculations. The strain was then calculated from the average displacement captured from three LVDTs (novotechniks) divided by the average specimen height.

Table 2. Summary of the cylinders varying tested parameters and age of testing

Specimen Group	ρ (%)	Number of specimens	Specimen Number (Age in days)
Plain UHPC	0	6	No. 1 (123), No. 2 (123), No. 9 (126), No. 10 (126), No. 18 (127), No. 19 (127)
1-in confined UHPC	1.91	5	No. 3 (123), No. 4 (123), No. 11 (126), No. 12 (126), No. 20 (127)
0.5-in confined UHPC	3.82	6	No. 5 (126), No. 6 (126), No. 13 (126), No. 14 (126), No. 21 (127), No. 22 (127)
0.25-in confined UHPC	7.63	5	No. 7 (126), No. 8 (126), No. 15 (127), No. 16 (127), No. 23 (127)

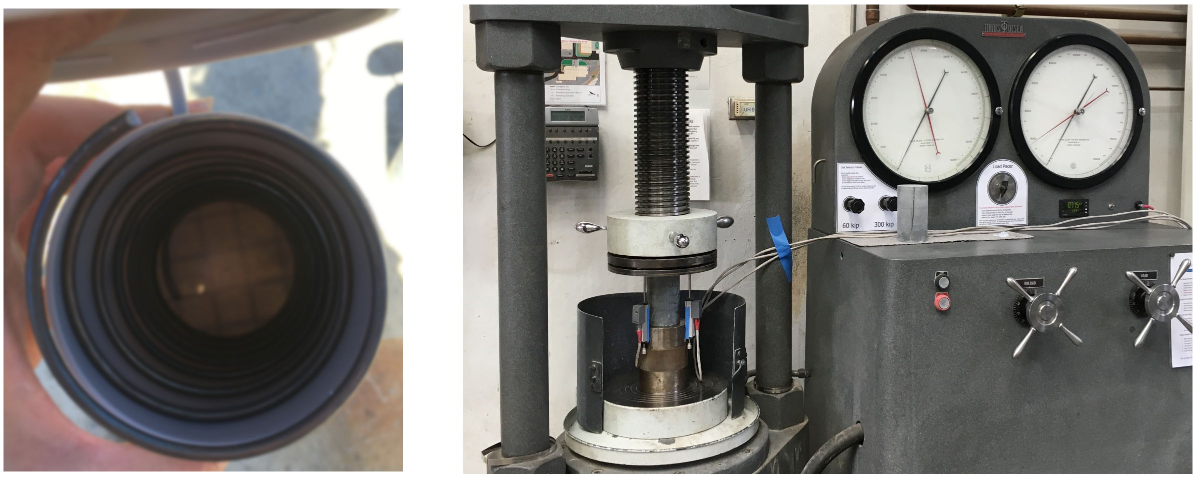
3.3. Instrumentation and test set-up

All the specimens were tested under uniaxial compression loading using a Tinius-Olsen 300 kip (1334 kN) compression testing machine under force control. The loading rate was constantly maintained at approximately 15 kip/min (67 kN/min). Three different novotechnik devices were placed around the perimeter with 120º angle in between as illustrated in Figure 1b to measure the axial shortening of the specimens. The axial load and the vertical displacement were both measured at sampling rate of 256 Hz.

4. Test results and discussion

Unconfined UHPC, also referred to as plain UHPC herein, cylinders typically failed by the gradual widening of multiple cracks in the vertical direction. In case of confined cylinders, the steel spirals stopped the progression and widening of the vertical cracks and prevented explosive failure of the specimens. The mode of failure for confined cylinders was a combination of small vertical cracks and spalling or crushing of UHPC in between the spirals. The typical failure mode of each group of UHPC specimens is illustrated in Figure 2.

To evaluate the ductility of the specimens, the ultimate strain was determined and compared for each group as shown in Table 3. The ultimate strain was defined as the strain at which the UHPC peak strength has already decreased by 20% [9]. Based on the results, the ultimate strains were equal to 0.0076, 0.0095 and 0.0103 for 1-in (25-mm), 0.5-in (13-mm) and 0.25-in (6-mm) confined cylinders, respectively. The increased strains reflect higher ductility which consistently increased by the increase of confinement ratio. It is noted that for plain UHPC specimens a sudden drop typically occurred after peak strength is reached and accordingly, an accurate post-peak behavior or ultimate strain values were not determined.



(a) **(b)**

Figure 1. (a) Typical steel spiral inside the mold, (b) Tinius-Olsen testing machine and novotechniks arrangement (one is behind the specimen)

(a) (b) (c) (d)

Figure 2. Typical failure mode of (a) unconfined (plain) UHPC, (b) 1-in confined UHPC, (c) 0.5-in confined UHPC and (d) 0.25-in confined UHPC cylinders

Table 3. Summary of test results

UHPC Specimen Group	**confinement ratio f'_l/f'_{co}**	***Modulus of Elasticity, E ksi (GPa)***	***Peak strength ksi (MPa)***	ε_p	$\varepsilon_{p,cc}/\varepsilon_{p,c}$	ε_{cu}	**confinement effectiveness f'_{cc}/f'_{co}**
Plain	-	6,585 (45.4)	29.90 (206)	0.0049	1.00	-	1.00
1-in confined	0.019	6,507 (44.9)	28.26 (195)	0.0050	1.04	0.0076	0.95
0.5-in confined	0.042	7,479 (51.6)	30.85 (213)	0.0058	1.20	0.0095	1.03
0.25-in confined	0.088	7,396 (51.0)	31.68 (218)	0.0066	1.37	0.0103	1.06

In Table 3, the confinement effectiveness is defined as the ratio of compressive strength of confined UHPC (f'_{cc}) to the unconfined compressive strength (f'_{co}). The confinement ratio is defined as the ratio of the effective lateral confining pressure (f'_l) to the unconfined compressive strength of plain UHPC (f'_{co}) using the following equation adopted from [11].

$$f_l' = \frac{1}{2} k_e \rho_s f_{yh}$$

where f_{yh} = yield strength of transverse steel; ρ = volumetric ratio of transverse confining steel to the confined concrete core; and k_e = confinement effectiveness coefficient, which in turn, is calculated as follows.

$$k_e = \frac{1 - \frac{s'}{2d_s}}{1 - \rho_{cc}}$$

where d_s = center-to-center diameter of spiral; s' = clear spacing between spiral wires (pitch) and ρ_{cc} = ratio of area of longitudinal steel to area of UHPC, which is zero for this study. The overall results indicates that confinement enhances the peak strength by about 6% (for 0.25-in confined UHPC) but increases the corresponding strain at peak strength by about 37%.

Moreover, Figure 3 shows a relation between the degree of out-of-planeness or distortion of cylinders versus the compression strength. Out-of-degree planeness of cylinders after grinding must be under 1 degree; otherwise, the specimen must be reground [12]. Based on Figure 3, all cylinders had out-of-planeness in the range of 0-0.5º, which had an insignificant impact on the compressive strength. As previously mentioned, the UHPC specimens were cast in 3×6 in (76×152 mm) cylinders but became shorter than what Ductal© suggests in the manual of Operating Procedures for Cylinders End-Grinding after grinding. Thus, the effect of height on the compressive strength of UHPC cylinders is investigated and summarized in Figure 4. Based on this figure, the height of specimen did not seem to have a trend that can affect the test results.

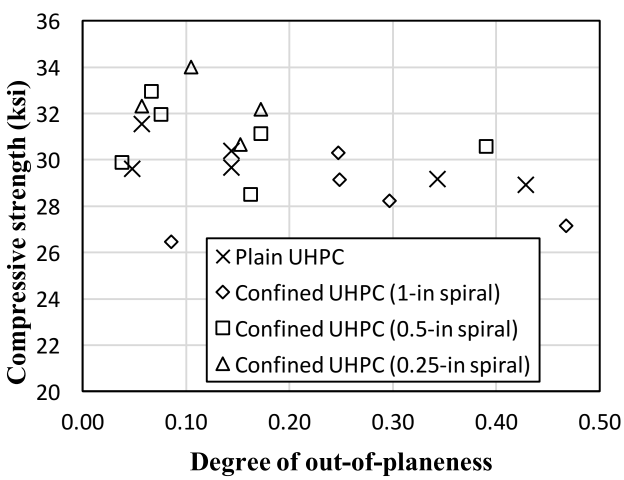


Figure 3. Compressive strength and cylinders end planeness of cylinders.

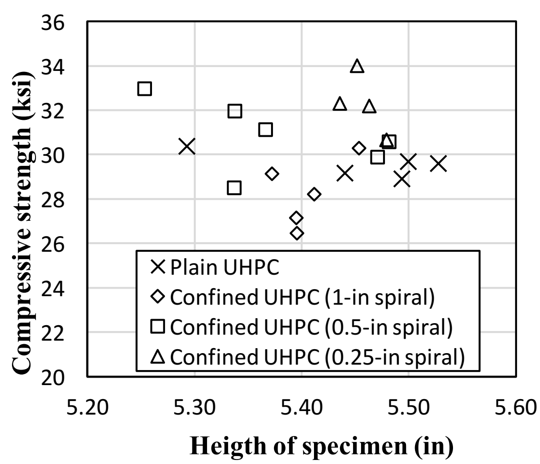


Figure 4. Compressive strength and height of cylinders.

The obtained stress-strain curves of plain UHPC, 1-in confined, 05-in confined, and 0.25-in confined UHPC cylinders are presented in Figures 5a through 5d, respectively. As shown in Figure 5d, the unconfined cylinders behave almost linearly until the peak strength which is followed by a sudden load drop that corresponds to an explosive failure. The confined cylinders show a smoother behavior as the peak strength is approached. The behavior of 1-in, 0.5-in and 0.25-in confined cylinders is also found to be almost linear up to 80%, 70%, and 60% of the peak strength, respectively (see Figure 5b-5d).

Similar to what Yang et. al. [9] observed, the confined stress-strain curves can be categorized to three different phases. The first phase is the elastic phase in which the transverse reinforcements are not yet active and the UHPC core mainly tolerate the load. In the second phase, small cracks and dilation of the UHPC core begin to occur, which in turn, activate the transverse reinforcements. Finally, in the last phase, UHPC reach its strength limit and a gradual load decrease starts. The shape of the curves in the second and third phases are apparently dependent on the volumetric ratio of the steel spirals. The higher the volumetric ratio of the steel spiral, the more energy dissipates through plastic deformations. This is exactly what is desirable for bridge columns designed for severe seismic loading. Therefore, confinement of UHPC columns can be beneficial as it is in conventional concrete columns to boost the ductility and strength of a cross-section.

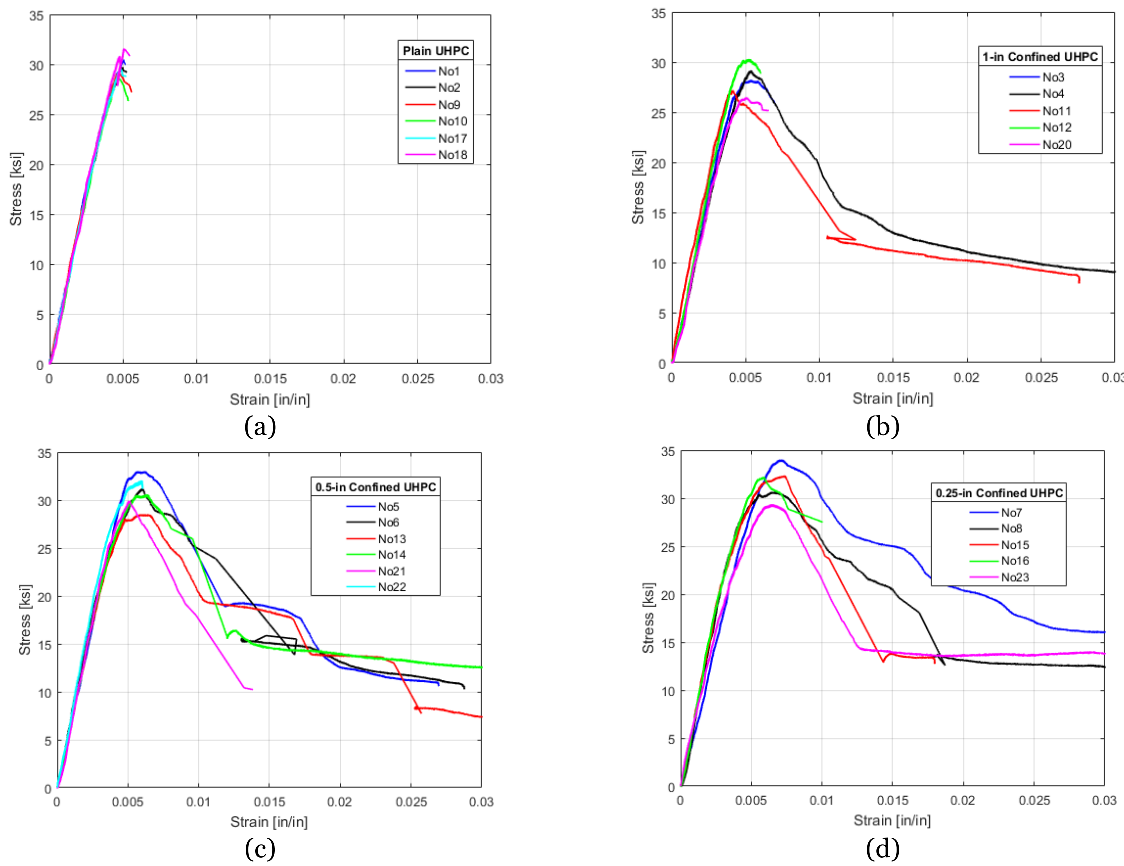


Figure 5. Stress-Strain response of (a) unconfined (plain) UHPC, (b) 1-in confined UHPC, (c) 0.5-in confined UHPC and (d) 0.25-in confined UHPC cylinders

5. Concluding Remarks

This paper presented the experimental tests on uniaxial compression behavior of unconfined UHPC and UHPC cylinders confined by steel spirals. The obtained and presented results include the stress-strain curves, modulus of elasticity, peak strength, and ultimate strain. Based on the test results, steel spirals improved the overall behavior of UHPC cylinders in term of strength and ductility. However, the ductility enhancement was more significant. The confinement effect of steel spirals is rendered in the stress-strain curves where the more confined UHPC cylinders showed higher plastic deformations. The obtained confined stress-strain curves could be categorized into three different zones: linear-elastic, nonlinear hardening, and softening phases, whereas the plain UHPC specimens demonstrated only an almost linear behavior up to the peak strength followed by a sudden drop.

Peak strength and ductility of confined specimens, compared to the unconfined ones, were quantitatively investigated by two parameters: confinement effectiveness ratio and ultimate strain. For the most confined specimens, i.e. 0.25-in confined cylinders, the confinement effectiveness ratio and ultimate strain were determined to be 1.06 and 1.03%, respectively. The results presented herein can be further used to inform finite element models of confined UHPC components. However, to have more statistically significant conclusions, more cylinders and tests need to be conducted, which motivated another experimental program that is currently undergoing.

6. References

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