# UHPC Compressive Strength Conversion Factors: Cubes Versus Cylinders

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**Abstract**
Higher demand for high early strength materials such as UHPC is on the rise especially for cases of rapid strength gain of more than 25 MPa after 12 hours, which help reduce construction time significantly in precast or ABC field applications. However, it is usually challenging, especially in remote sites, to test UHPC cylinders at early age such as 12 or 14 hours due to the required cylinders preparation and end grinding. At early ages or relatively low strength levels, compression test results are very sensitive to cylinders preparation and grinding, and there might be even discrepancies in the results due to the quality of the surface cutting and grinding procedure. The operations performed on cylinders at an early age affect the results and weaken the specimens. Thus, cubes could be used as an alternative to cylinders at least for on-site and early age quality control purposes. Cubes do not require operations before testing, hence leading to consistent results. This paper presents a comprehensive study that uses results from about 900 cubes and cylinders of five different UHPC mixtures with varying steel fiber content and curing regimes. Cubes and cylinders from same batches were tested and compared to deduce robust conversion factors between different cube sizes (2-inch and 4-inch cubes) and the standard 3×6 inch cylinder. The proposed conversion factors accounts for different ages and strength range, and as such, can be used for a wide range of strength that covers 1 to 20 ksi (7 to 140 MPa) range.

**Keywords:** UHPC, compressive strength, cubes, cylinders, conversion factor, quality control

## 1. Introduction

With the high demands of constructing and maintaining buildings and bridges, the demand for high strength materials increases. High strength materials offer rapid strength gain in a short time which result in reducing construction time, thus reducing the potential of long roads shutdown and traffic delays. An example of a widely used high strength and high performance material for accelerated construction projects is ultra-high performance concrete (UHPC). UHPC is a cementitious material characterized by durability, long-term stability, and high compressive strength (Graybeal 2006). UHPC can reach a compressive strength of 10 ksi (69 MPa) after 24 hours and 22 ksi (152 MPa) after 28 days of casting if a specific curing procedure is followed. The compressive strength of UHPC could exceed seven times the strength of conventional concrete, and the modulus of the elasticity of UHPC could exceed the double of conventional concrete (Graybeal 2006; Naeimi and Moustafa 2021).

Further, when casting UHPC, cylinders are supposed to be delivered to the labs to be tested in compression as a quality control method to verify the strength of the UHPC (ASTM C1856). In the United States, the standardized cylinder for UHPC compression testing is 75 mm in diameter × 150 mm in height (3 in × 6 in) (ASTM C1856). However, cylinders require specific operations before testing in compression, such as cutting and grinding the surfaces. Such processes consume time and sometimes, require fully equipped labs that can provide high-capacity compression machines, grinding machine, and cutting machine. Furthermore, in remote construction sites, contractors will likely establish a materials lab on the site; thus, more costs are directed toward the machines and consumed time if cylinders are used for early age quality control on site. To save the costs and time consumed in preparing the cylinders, cubes could be an alternative. Some countries use cubes for both standard strength characterization as well as quality control testing, like China, where the standard quality control specimen in compression is the 100 mm × 100 mm × 100 mm (4 in × 4 in × 4 in) (CECS 13: 2009). The main advantage of using cubes is that they do not require special operations such as cutting and grinding the faces. To use specimens other than the standardized 75 mm × 150 mm cylinders for UHPC, a dedicated study that accounts for different specimens shapes and sizes and uses wide range of UHPC mixtures should be performed to develop precise conversion factors between the different shapes and sizes.

Graybeal (2015) studied the effect of various specimens' shapes and sizes on the compressive strength of one UHPC proprietary mix with 6% fibers by weight. The research used: 50-, 75-, and 100-mm (2-, 3-, and 4-inch) diameter cylinders with a height-to-diameter ratio of 2, and 50- and 100-mm (2- and 4-inch) cubes. The study found that the smaller specimen sizes showed larger standard deviations than the bigger specimens; thus, it was not recommended to use specimens smaller than 75 mm (3 in). In an earlier study, Graybeal and Davis (2006) studied different sizes of cubes and cylinders UHPC specimens. The specimen's sizes were: 76 and 102 mm (2, 3, and 4 in) cylinders and 50-, 70-, and 100-mm (2-, 2.78-, and 4-in.) cubes, and they used three UHPC mixtures. Two different mixtures have 2% fiber by volume, and the third has no fibers. Two different curing conditions were adopted. They tested the cubes and cylinders at 3, 4, 9, 27, and 28 days after casting to have a different compressive strength level ranging from 80 to 200 MPa (11.6 to 29.0 ksi). They determined that the conversion factors to be 1.00 and 0.96 to convert the 100 mm cubes and 50 mm cubes results to 75 mm cylinder, respectively. The study also recommends using a 70 mm (2.78 in) cube as opposed to the 50 mm cylinders and cubes due to their large strength variations compared with the other sizes.

The literature covered conversion factors starting from 11.6 ksi or three days. However, this high compressive strength values only appear at later ages, which is not the case for the 12 hours or one day strength when ABC applications are considered. Thus, the conversion factors in the literature might be valid at a late age or when the material has already gained most of its strength, but the question still remains on what cube conversion factors can be used at one day or less. For example, when a bridge can operate when field joint concrete strength reaches a threshold of 8000 psi (55 MPa) (Lee et al. 2014), UHPC can get there in less than one day. Thus, the proposed factors in the literature need to be revisited and checked whether they are valid at early ages. Moreover, limited published data can be used to capture both conversion factors for lower strength as well as more generalized ones that could be valid for all ages or all strength levels. One more limitation in the literature is that previous research has used less types of UHPC mixtures, which do not cover non-proprietary mixes (Abokifa and Moustafa 2021) or emerging UHPC types such as carbon nanofibers enhanced UHPC (Cimesa and Moustafa 2022).

Based on above, this paper extends the previous efforts by using a wide range of UHPC types that are now available in the construction market. This paper investigates the applicability of using 50 mm and 100 mm cubes as an alternative to the standardized 75 mm cylinders. For such an objective, different proprietary and non-proprietary UHPC mixtures were used. The proprietary mixtures used in this research are widely used in the United States as well as internationally. Five UHPC mixtures were used, and around 900 specimens of cubes and cylinders were tested at early and late ages to cover a compressive strength range of 7 MPa to 140+ MPa (1 ksi to 20+ ksi).

## 2. Experimental Program

The experimental campaign includes both proprietary and non-proprietary UHPC mixtures. The UHPC used in this research are referred to as: UHPC type A with 1% steel fibers, UHPC type B with 1% and 2% steel fibers, UHPC type C with 1% and 2 % steel fibers, UHPC type D with 2% steel fibers, and UHPC type E with 2% fibers with and without accelerator. The proportions of the UHPC mixtures are shown in Table 1. The specimens' shapes and sizes that were studied in this research are: (1) 75 mm in diameter × 150 mm in height (3 in × 6 in) cylinders denoted herein as 75 mm cylinders or (3×6), (2) 100 mm × 100 mm × 100 mm (4 in × 4 in × 4 in) cubes indicated herein by 100 mm cube or (4×4), and (3) 50 m × 50 mm × 50 mm (2 in × 2 in × 2 in) cubes denoted herein by 51 mm cubes or (2×2). The UHPC molds and samples of different shapes and sizes used in this research are shown in Figure 1b. Additional details of the proportions of the UHPC mixtures used in this study and temperature histories of the specimens from the sensors can be found in Ibrahim (2022) and Ibrahim and Moustafa (2022).

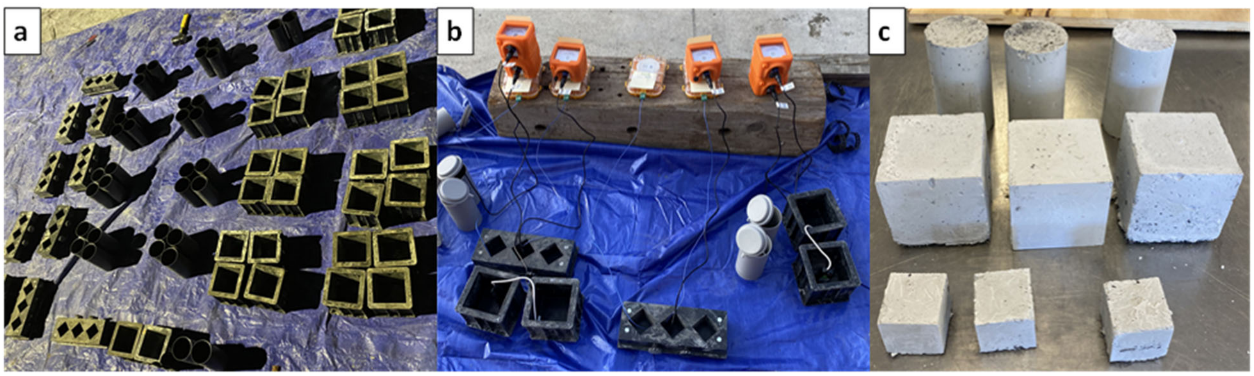


**Figure 1. (a) Different specimen molds; (b) small cube molds and maturity sensors; and (c) specimens after being removed from the molds.**

**Table 1. Constituents the different UHPC mixtures used in this research.**

| Constituents ($lb/yd^3$) | | UHPC A | UHPC B-1% and 2% | UHPC C-1% | UHPC C-2% | UHPC D | UHPC E |
|---|---|---|---|---|---|---|---|
| Type I Cement | | 1179.6 | - | - | - | 1269 | - |
| Slag | | 589.8 | - | - | - | - | - |
| Silica fumes | | 196.6 | - | - | - | - | - |
| Fine masonry sand | | 1966 | - | - | - | 1350 | - |
| Steel fibers* | 1% | 132.3 | 132.3 | 133 | - | - | - |
| | 2% | - | 264.6 | - | 264 | 265 | 263.8 |
| Superplasticizer | | 22.12 | 16.54 | - | - | 60.75 | 50.32 |
| Corrosion plasticizer | | - | - | - | - | 22.82 | - |
| workability plasticizer | | - | - | - | - | 47.25 | - |
| water | | 393.2 | 199.8 | 274.1 | 271.4 | 243 | 171.8 |
| Premix | | - | 3600 | 3916 | 3876 | 1080 | 3681.8 |
| Ice | | - | 133.2 | - | - | - | - |
| Accelerator | | - | - | 39.2 | 38.8 | - | 12.27 |
| Nano-fibers | | - | - | 22.5 | 22.3 | - | - |

* The presented fibers percentage are by volume

The cast specimens were divided into two groups: the first group was cured in standard laboratory curing room until testing (indicated herein as lab cured or L in the tables below) according to ASTM C511-21. The second group was left in the fabrication yard outside the University of Nevada, Reno Structures and Earthquake Engineering Laboratories until testing to mimic the conditions of the construction site (indicated herein as site cured or S in tables). The casting of the different UHPC mixtures and specimens took place over the course of almost a full year in Reno, Nevada, where the weather conditions varied from hot and dry in the summer to cold, rainy, and snowy in the winter. As stated in the literature review above, the temperature and curing conditions might affect the conversion factors; thus, a wide range of temperatures was considered. In addition, some specimens were placed in the oven for 12 hours at a temperature of 104°F (40°C) to represent heat curing conditions. To measure and track the temperature of the specimens, three temperature (maturity) sensors from three different vendors were used to measure and store the temperature (see Figure 1b).

Before testing the UHPC cylinders, flat and parallel surfaces are required, which in turn, requires special preparations such as cutting the top surface and then grinding both the top and bottom surfaces. After demolding and preparing the different cubes and cylinders, all specimens were tested under compression load at a 500-kip Machine. Figure 2 shows pictures from three different specimens types considered in this study. The cylinder specimens were tested according to ASTM C39 and the cubes specimens were tested according to ASTM C109. The loading rates were modified because of the high strength of UHPC that could take a long time to break, but followed what was recommended by Graybeal (2014), who studied the influence of increasing the loading rates on the compressive strength results and found that it did not influence the results.

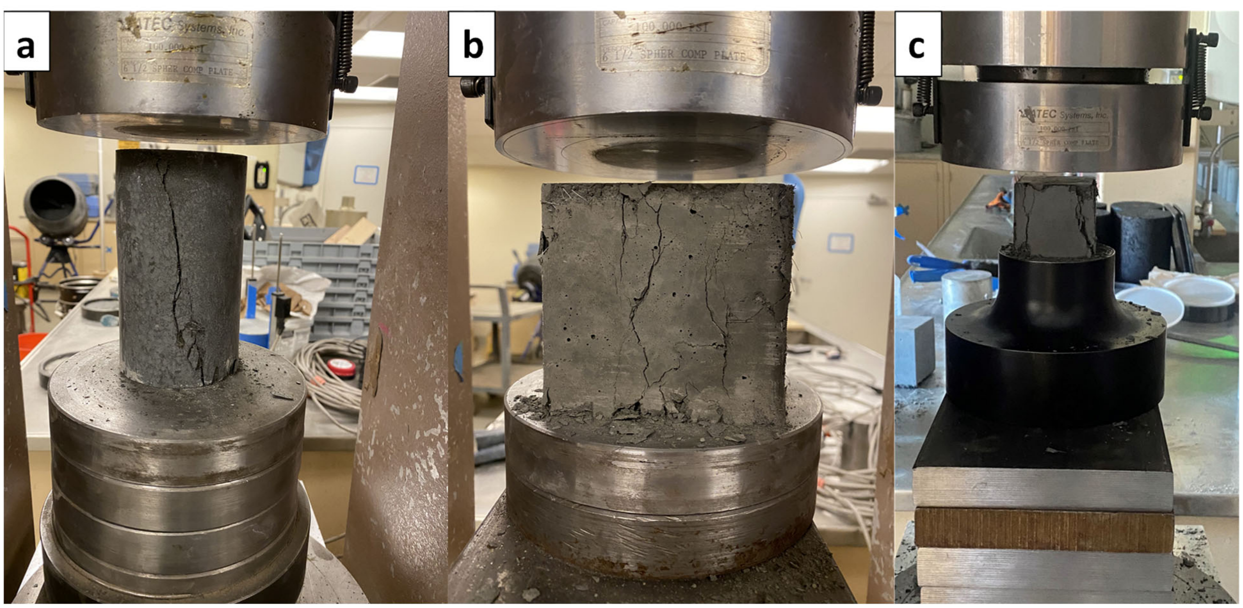


**Figure 2. Typical UHPC compression tests using: (a) 3 x 6 in cylinders, (b) 4-inch cubes, and (c) 2-inch cubes.**

## 3. Conversion Factors of Compressive Strength between Cubes and Cylinders

The cylinders and cubes specimens were tested from 14 hours to 28 days. The compressive strength range covered from less than 7 MPa to over 140 MPa. Such range expands beyond the data range covered in the literature. The conversion factors between the 75 mm cylinders, the 50 mm, and the

100 mm cubes were obtained and reported for all tested specimens. At each age, at least three specimens were tested in compression. The average of the three values, standard deviation, and variance was calculated and just a sample of the results as obtained from two UHPC mixtures is reported in Table 2. Furthermore, to calculate the conversion factors and functions, the least-squares method was used. Three functions were calculated: the first function is a linear regression that included an intercept, the second is a linear regression function without an intercept (zero intercepts), and the third function is a power function. All three regression-based or best fitted functions were determined and summarized along with their $R^2$ in Table 2.

**Table 2. Sample of the obtained compressive strength, standard deviation and coefficient of variation of the different UHPC specimens types**

| Time [days] | | Compressive Strength, MPa | | | Standard Deviation, MPa | | | Coefficient of Variation | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 75 mm cylinder | 100 mm cube | 50 mm cube | 75 mm cylinder | 100 mm cube | 50 mm cube | 75 mm cylinder | 100 mm cube | 50 mm cube |
| ***UHPC Type A*** | | | | | | | | | | |
| **Lab** | 0.6 | 16.0 | 18.5 | 13.6 | 1.01 | 0.60 | 0.41 | 2.13 | 0.76 | 0.35 |
| | 0.7 | 29.1 | 29.4 | 18.7 | 1.60 | 1.38 | 2.00 | 5.37 | 4.02 | 8.41 |
| | 0.9 | 33.2 | 27.4 | 32.2 | 2.05 | 1.20 | 1.21 | 8.83 | 3.03 | 3.08 |
| | 1.0 | 47.3 | 42.9 | 44.8 | 1.25 | 1.05 | 1.23 | 3.3 | 2.33 | 3.2 |
| | 2.0 | 68.4 | 55.1 | 36.4 | 0.40 | 2.28 | 2.25 | 0.33 | 10.9 | 10.68 |
| | 3.2 | 83.0 | 67.7 | 42.6 | 3.00 | 1.45 | 0.78 | 18.89 | 4.4 | 1.28 |
| | 7.1 | 97.4 | 69.5 | 66.3 | 1.37 | 1.53 | 0.50 | 3.95 | 4.92 | 0.53 |
| | 14.0 | 104.2 | 81.2 | 80.8 | 0.12 | 2.62 | 3.98 | 0.03 | 14.39 | 33.28 |
| | 28.2 | 114.1 | 89.7 | 79.8 | 5.63 | 1.58 | 5.05 | 66.7 | 5.23 | 53.54 |
| **Site** | 2.0 | 74.2 | 52.6 | 47.5 | 2.33 | 1.37 | 0.41 | 11.38 | 3.97 | 0.36 |
| | 3.2 | 73.3 | 70.8 | 37.9 | 2.59 | 0.88 | 1.63 | 14.05 | 1.64 | 5.58 |
| | 7.1 | 89.7 | 80.2 | 69.9 | 3.09 | 6.59 | 4.76 | 20.14 | 91.46 | 47.7 |
| ***UHPC Type B*** | | | | | | | | | | |
| **Lab** | 0.6 | 25.9 | 48.5 | 10.6 | 0.35 | 0.97 | 0.43 | 0.26 | 1.97 | 0.39 |
| | 0.7 | 48.7 | 52.0 | 29.5 | 3.57 | 2.78 | 1.82 | 26.79 | 16.2 | 6.93 |
| | 0.8 | 61.5 | 56.2 | 37.6 | 3.21 | 2.44 | 1.63 | 21.64 | 12.49 | 5.55 |
| | 1.0 | 63.1 | 66.0 | 58.6 | 3.55 | 0.04 | 1.02 | 26.45 | 0 | 2.21 |
| | 2.1 | 84.0 | 65.3 | 81.9 | 1.40 | 4.62 | 4.28 | 4.12 | 44.93 | 38.55 |
| | 3.0 | 90.6 | 82.7 | 102.4 | 3.41 | 6.20 | 7.38 | 24.47 | 80.73 | 114.56 |
| | 7.1 | 107.5 | 80.0 | 94.8 | 4.75 | 1.61 | 1.67 | 47.43 | 5.48 | 5.84 |
| | 14.0 | 123.5 | 87.3 | 83.7 | 7.91 | 0.98 | 1.65 | 131.75 | 2.04 | 5.73 |
| | 28.1 | 134.0 | 96.6 | 105.4 | 3.38 | 3.29 | 7.47 | 24.07 | 22.77 | 117.21 |
| **Site** | 1.0 | 73.1 | 54.8 | 53.4 | 1.78 | 2.09 | 3.31 | 6.68 | 9.21 | 23.04 |
| | 2.0 | 76.4 | 66.4 | 76.9 | 4.08 | 2.98 | 3.00 | 35 | 18.69 | 18.92 |
| | 3.0 | 89.0 | 74.1 | 90.8 | 0.21 | 5.32 | 3.71 | 0.09 | 59.57 | 28.96 |

**Table 3. Conversion factors and functions of compressive strength**

| | 100 mm cubes to 75 mm cylinders | | 50 mm cubes to 75 mm cylinders | | 50 mm cubes to 100 mm cubes | |
|---|---|---|---|---|---|---|
| | Function | $R^2$ | Function | $R^2$ | Function | $R^2$ |
| Linear without intercept | 1.2x | 0.94 | 1.1x | 0.89 | 0.9x | 0.83 |
| Linear with intercept | 1.3x - 5.7 | 0.94 | 1.1x + 6.2 | 0.9 | 0.8x + 12.1 | 0.86 |
| Power function | $0.86x^{1.1}$ | 0.96 | $1.04x^{1.03}$ | 0.91 | $1.5x^{0.9}$ | 0.87 |

The conversion factors along with the different proposed regression functions presented above in Table 3 can be readily used for any range of UHPC strength at both early and late ages. However, to further present such data and provide a visual demonstration of the validity of the proposed equations, Figures 3a, 3b, and 3c plot the compression strength of 3-inch cylinder versus 2-inch cubes, 3-inch cylinders versus 4-inch cubes, and 4-inch versus 2-inch cubes, respectively. The figures also show the three different deduced functions against the individual data points obtained from the large number of tested cubes and cylinders.

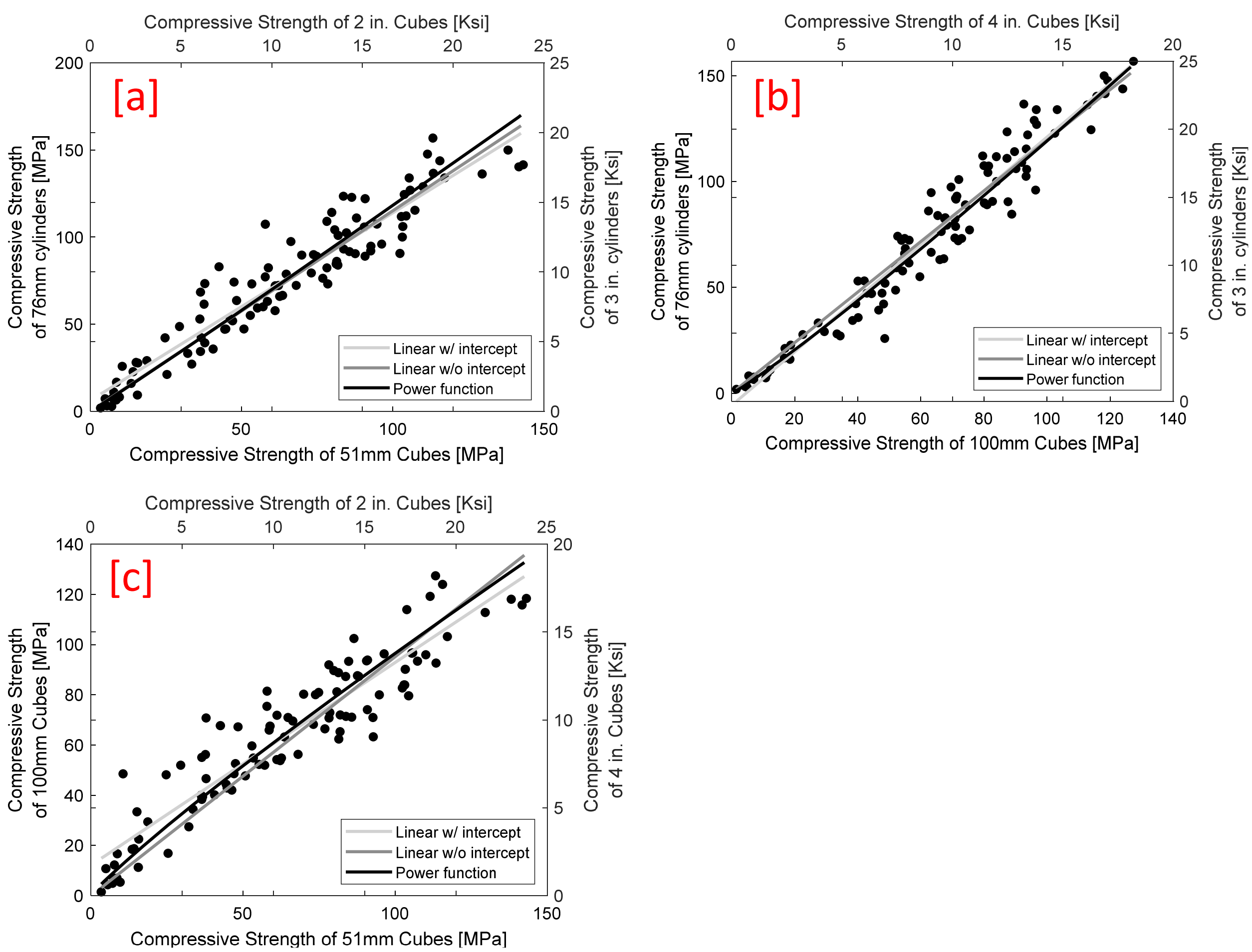


**Figure 3. Compression strength and conversion: (a) between 2-inch cubes to 3-inch cylinders; (b) between 4-inch cubes to 3-inch cylinders; and (c) between 2-inch cubes to 4-inch cylinders**

## 3. Conclusions

The main goal of the current study was to extend the previous efforts in the literature and provide a robust conversion factors covering a wider range of strength levels in addition to using more UHPC mixtures that are widely used nowadays. The results showed that the 2-inch (50 mm) cubes showed a high discrepancy at low strength levels (early ages) when converting their results to 4-inch (100 mm) cubes and 3-inch (75 mm) cylinders. However, the discrepancies were reduced when the strength level exceeds ~8.7 ksi (~60 MPa). Thus, it is not recommended to use 2-inch (50 mm) cubes for early age quality control purposes or when the expected strength level is less than 8.7 ksi (60 MPa). Moreover, low discrepancies were observed when converting from the 4-inch (100 mm) cubes to 3-inch (75 mm) cylinders at all strength levels, i.e. for all ages. Therefore, the 4-inch (100 mm) cubes can be used with confidence for determining UHPC strength at any stage, and as such, it is recommended to consider the 4-inch (100 mm) cubes for on-site quality control and early age strength determination.

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## 5. References

- Abokifa, M., & Moustafa, M. A. (2021). Mechanical characterization and material variability effects of emerging non-proprietary UHPC mixes for accelerated bridge construction field joints. Construction and Building Materials, 308, 125064.
- ASTM C511-21. Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. https://doi.org/10.1520/C0511-21.
- ASTM C1856. "Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete." ASTM International, vol. i, 2017, p. 4, https://doi.org/10.1520/C1856.
- Cimesa, M., & Moustafa, M. A. (2022). Experimental characterization and analytical assessment of compressive behavior of carbon nanofibers enhanced UHPC. Case Studies in Construction Materials, 17, e01487.
- Graybeal, B. "Material Property Characterization of Ultra-High Performance Concrete." FHWA, no. FHWA-HRT-06-103, 2006, p. 186.
- Graybeal, B., & Davis, M. (2008). 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), 603.
- Graybeal, Benjamin A. "Compression Testing of Ultra-High-Performance Concrete." Advances in Civil Engineering Materials, vol. 4, no. 2, 2015, pp. 102–112.

- Lee, C., George, et al. Seismic Performance Evaluation of Precast Girders with Field-Cast Ultra High Performance Concrete (UHPC) Connections - MCEER: Earthquake Engineering to Extreme Events - University at Buffalo. 2014, pp. 1–242.
- Ibrahim, M.S. (2022). Robust Methods for UHPC Early-Strength Determination and Quality Control for Accelerated Bridge Construction. MS Thesis, University of Nevada, Reno
- Ibrahim, M.S., & Moustafa, M.A. (2022). Strength Maturity Method for Quality Control of Field-Cast UHPC Seismic Accelerated Bridge Construction Connections, 12NCEE, Salt Lake City, UT
- Naeimi, N., & Moustafa, M. A. (2021). Analytical stress–strain model for steel spirals-confined UHPC. Composites Part C: Open Access, 5, 100130.
- Naeimi, N., & Moustafa, M. A. (2021). Compressive behavior and stress–strain relationships of confined and unconfined UHPC. Construction and Building Materials, 272, 121844.
- Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens 1. https://doi.org/10.1520/C0039_C0039M-21.
- Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 Mm] Cube Specimens) 1. https://doi.org/10.1520/C0109_C0109M-21.
- Standard Test Methods for Fiber Reinforced Concrete (in Chinese), CECS 13: 2009, 2009. https://www.chinesestandard.net/PDF/BOOK.aspx/CECS13-2009.