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Cylinder or Cube: Strength Testing of 80 to 200 MPa (11.6 to 29 ksi) Ultra-High-Performance Fiber-Reinforced Concrete

by Benjamin Graybeal and Marshall Davis

Accurate determination of the compressive strength of very high strength concrete is currently a difficult proposition due to large testing machine capacity requirements and the need for cylinder end preparation. An experimental program was conducted to determine whether alternate specimen types can be reliably used to determine the compressive strength of an ultra-high-performance fiber-reinforced concrete (UHPFRC) in the strength range from 80 to 200 MPa (11.6 to 29 ksi). Fifty-one, 76, and 102 mm (2, 3, and 4 in.) cylinders were tested alongside 51, 70.7, and 100 mm (2, 2.78, and 4 in.) cube specimens. The 76 mm (3 in.) cylinder as well as the 70.7 and 102 mm (2.78 and 4 in.) cubes were found to be acceptable alternatives to the standard 102 mm (4 in.) cylinder specimen. The 70.7 mm (2.78 in.) cube specimen is recommended for situations where machine capacity and/or cylinder end preparation are of concern.

Keywords: compressive strength; cube; cylinder; ultra-high-performance fiber-reinforced concrete.

INTRODUCTION

The continued advancement of concrete technology and the associated push to adapt advanced technology to production processes has resulted in the initial uses of 205 MPa (30 ksi) compressive strength concrete in the constructed environment.[1,2] Producing concretes of this strength level presents a set of challenges to the concrete industry, many of which can be termed quality control/quality assurance issues. In North America, cylinder compressive strength is widely used as a proxy for any number of other concrete properties, in addition to its obvious role relating to the compressive strength of the structural concrete. In the history of modern structural concrete, compressive strength is one of the most, if not the most, important property in terms of verifying acceptability of a wide range of concrete behaviors to a structure's performance. Accurately and reliably verifying the compressive strength of a 200 MPa (29 ksi) concrete, however, can be a challenge in and of itself.

The two standard methods for determining the compressive strength of concrete are the testing to failure of cylinder and cube specimens. National codes and specifications in North America, France, Japan, Australia, and New Zealand define the cylinder as the standard specimen, whereas much of the remainder of Europe relies on the cube specimen.[3,4] Around the world, cube and cylinder specimens of varying sizes are accepted as the standard representation of the compressive strength of concrete in a structural member.

The two primary issues that arise regarding the extension of standard concrete compression test methods to very high strength concretes are testing machine capacity and cylinder end preparation. Barring the purchase of high load capacity testing machines, the simple solution to the first issue is to use smaller specimens. Barring the purchase of expensive cylinder end grinding equipment, the simple solution to the second issue is to use cube specimens. The combination of these solutions, however, effectively moves away from standard practice in the concrete industry and raises concerns the about the accuracy and reliability of the test results.

Many studies going back over 80 years to Gonnerman[5] have investigated the relationship between various cylinder and cube sizes on the compressive strength of concrete. For standard concrete mixture designs at normal compressive strength levels, it is normally assumed that cubes will relate a higher compressive strength (up to 25%), but the difference will decrease at increasing strength levels.[4] When comparing different sizes of specimens, researchers have demonstrated that, at normal strength levels, the smaller specimens tend to present higher compressive strengths. This result has been theorized to be due to larger specimens having a greater likelihood of containing elements of low strength.[4]

There have been a series of research efforts in the last 25 years focused on similar issues to those addressed in the current research effort with what would now be considered high-strength concrete. Papers by Nasser and Al-Manaseer[6] and Nasser and Kenyon[7] pushed for an acceptance of the 76 mm (3 in.) diameter cylinder as a standard compressive strength specimen. Day[8] compiled research results from 22 separate studies to perform statistical analyses on the relationship between 76, 102, and 152 mm (3, 4, and 6 in.) cylinders. Issa et al.[9] investigated specimen size effects with 51 to 152 mm (2 to 6 in.) cylinders. Aïtcin et al.[10] investigated cylinder strength results for concretes up to 120 MPa (17.5 ksi). Mansur and Islam[11] investigated the relationship between cylinders and cubes of 100 and 150 mm (4 and 6 in.) minimum dimension and compressive strengths up to 100 MPa (14.5 ksi). The results of these investigations are generally similar in that the strength expressed by smaller cylinders and/or cubes is expected to be slightly higher than the strength expressed by the 152 mm (6 in.) diameter cylinder, and that strength differences will decrease at higher compressive strength levels.

The present research effort is intended to extend the applicability of the previous research on this topic into the realm of the new advanced cementitious materials that have become commercially available in the last decade.[12,13] These and other similar concretes are generally classified as ultra-high-performance fiber-reinforced concrete (UHPFRC), with very high compressive strengths, usable pre- and post-cracking tensile strengths, and significantly improved durability properties as compared with conventional concretes.

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Table 1—UHPFRC mixture design

Material	Mixture Design 1 amount, kg/m^3	Mixture Design 2 amount, kg/m^3	Mixture Design 3 amount, kg/m^3
Premix*	2195	2175	2317
Portland cement	718	711	758
Fine sand	1029	1019	1086
Silica fume	234	232	247
Ground quartz	212	210	224
High-range water-reducing admixture	30	30	31
Accelerator	26	26	27
Steel fibers	156	155	0
Water	112	134	143

*Premix is composed of the four succeeding items.
Note: 1 lb/yd^3 = 0.593 kg/m^3.

Table 2—Premix age, mixture design, curing, and testing age

Batch	Premix age at casting, months	Mixture design	Curing regime	Testing age, days
QZ	2.5	1	96 hours, 95 °C, 95% humidity	28
QU	8	2	48 hours, 90 °C, 95% humidity	28
QB	3	1	48 hours, 90 °C, 95% humidity	27
QC	2	1	48 hours, 80 °C, 95% humidity	28
QD	1.5	1	48 hours, 60 °C, 95% humidity	28
QR	12	3	48 hours, 90 °C, 95% humidity	28
QS	12.5	3	48 hours, 60 °C, 95% humidity	28
QV	7.5	2	48 hours, 40 °C, 95% humidity	28
QE	3	1	Lab environment	28
QW	7	2	48 hours, 22 °C, 95% humidity	28
QQ	7	3	Lab environment	28
QF	3.5	1	Lab environment	9
QG	4	1	Lab environment	4
QX	6.5	2	Lab environment	3

From a practical standpoint, the compressive strength testing of a 152 mm (6 in.) cylinder composed of one of these concretes may require both a 4500 kN (1000 kip) compression machine and a cylinder end grinder, thus making the testing of this concrete a specialized task only possible in select testing laboratories. Using the compressive strength as a proxy for the development of other properties thus becomes more difficult and expensive.

Two countries currently have design guidelines pertaining to the structural use of this type of concrete. The French specification[14] suggests the use of either 70 or 110 mm (2.75 or 4.3 in.) cylinders to determine the compressive strength, whereas the Japanese specification[15] suggests the use of 100 mm (4 in.) diameter cylinders. In other parts of the world, 102 mm (4 in.) or larger least-dimensioned cylinders or cubes are required according to the relevant existing structural design specifications. In the U.S., 102 mm (4 in.) diameter cylinders are the accepted standard specimen size.

Only two previous studies have specifically investigated the use of smaller-dimensioned cubes to represent the compressive strength of 102 mm (4 in.) or larger cylinders in this very high compressive strength range. The data from these studies, one by the present author[16] and one completed by Ahlborn and Kollmorgen,[17] is included in the analysis performed on the data collected as part of the present study.

RESEARCH SIGNIFICANCE

This paper investigates the relationship between the measured compressive strength of UHPFRC as expressed by three sizes of cylinder specimens and three sizes of cube specimens. Use of these types of concrete by the concrete industry at large will be hampered unless practical tests to accurately determine the compressive strength are developed. The research discussed herein focuses on determining the viability of using reduced-dimension cube specimens for the measurement of concrete compressive strength.

EXPERIMENTAL INVESTIGATION

Six different cube and cylinder specimens were investigated. Fifty-one, 76, and 102 mm (2, 3, and 4 in.) cylinders were tested alongside 51, 70.7, and 100 mm (2, 2.78, and 4 in.) cube specimens. The compressive strength of the concrete tested ranged from 80 to 200 MPa (11.6 to 29 ksi).

In North America, there is currently only one UHPFRC that is commercially available and as such, it was used in this research program. This high cement, high silica fume content concrete has an extremely low water-cement ratio (*w/c*) and uses a polycarboxylate-based high-range water-reducing admixture to obtain an acceptable workability. This concrete contains no coarse aggregate, with the largest nonfiber constituent being a fine (<600 micrometer diameter) sand. The mixture designs are provided in Table 1, with Mixture Design 1 being the standard mixture design, Mixture Design 2 being a modified design with higher water-cementitious material ratio (*w/cm*), and Mixture Design 3 being a modified version of Mixture Design 2 wherein the fiber reinforcement was eliminated. Mixture Designs 1 and 2 were internally reinforced at 2% by volume with 13 mm (0.5 in.) long, 0.2 mm (0.008 in.) diameter straight steel fiber reinforcement.

Fourteen sets of cylinder and cube specimens were fabricated in batches listed in Table 2. The range of compressive strengths over which the batches cover were obtained by fabricating the specimens at various ages after premix blending, by testing the concretes at various ages after casting, and through the application of different curing regimes to the cast concrete. All sets were fabricated between 1.5 and 12.5 months after premix blending and were tested between 3 and 28 days after fabrication. The curing regimes ranged from maintaining the specimens in a laboratory environment until testing to subjecting the specimens to 96 hours of 95 °C (203 °F) and 95% humidity conditions.

Table 3—Fiber-reinforced cylinder and cube test results

Batch	Type	Size, mm	Compressive strength			95% confidence	
			Average, MPa	Standard deviation, MPa	Coefficient of variation	Lower, MPa	Upper, MPa
QZ	Cube	100	198.1	4.9	0.0249	192.9	203.3
	Cube	70.7	231.1	5.0	0.0218	225.8	236.4
	Cube	51	233.7	6.3	0.0270	227.0	240.3
	Cylinder	102	202.9	7.3	0.0362	195.2	210.6
	Cylinder	76	209.5	11.1	0.0529	197.9	221.2
	Cylinder	51	203.3	17.3	0.0853	185.1	221.5
QU	Cube	100	189.1	6.4	0.0339	182.4	195.9
	Cube	70.7	210.1	4.8	0.0227	205.0	215.1
	Cube	51	206.8	2.0	0.0096	204.7	208.9
	Cylinder	102	197.8	7.8	0.0396	189.5	206.0
	Cylinder	76	203.7	7.8	0.0381	195.6	211.9
	Cylinder	51	179.6	8.3	0.0462	170.9	188.3
QB	Cube	100	190.9	5.9	0.0311	184.7	197.1
	Cube	70.7	216.1	7.4	0.0345	208.3	223.9
	Cube	51	216.1	5.8	0.0269	210.0	222.2
	Cylinder	102	198.5	3.8	0.0193	194.5	202.6
	Cylinder	76	199.3	7.9	0.0398	190.9	207.6
	Cylinder	51	186.5	6.4	0.0344	179.8	193.2
QC	Cube	100	186.6	5.2	0.0277	181.2	192.0
	Cube	70.7	204.4	8.1	0.0397	195.9	212.9
	Cube	51	205.9	6.8	0.0331	198.8	213.1
	Cylinder	102	182.6	6.4	0.0350	175.9	189.3
	Cylinder	76	197.3	5.1	0.0257	192.0	202.6
	Cylinder	51	188.7	8.7	0.0461	179.6	197.8
QD	Cube	100	170.8	5.3	0.0308	165.3	176.3
	Cube	70.7	193.2	5.1	0.0266	187.8	198.5
	Cube	51	195.9	5.5	0.0278	190.2	201.6
	Cylinder	102	176.8	3.4	0.0192	173.2	180.3
	Cylinder	76	179.9	7.9	0.0441	171.6	188.2
	Cylinder	51	179.2	6.0	0.0335	172.9	185.5
QV	Cube	100	153.8	3.8	0.0245	149.8	157.7
	Cube	70.7	156.3	1.5	0.0094	154.7	157.8
	Cube	51	157.8	3.9	0.0247	153.7	161.9
	Cylinder	102	150.2	3.2	0.0216	146.8	153.6
	Cylinder	76	147.5	7.1	0.0479	140.1	154.9
	Cylinder	51	134.9	6.8	0.0504	127.8	142.1
QE	Cube	100	141.5	2.8	0.0200	138.6	144.5
	Cube	70.7	145.9	4.0	0.0275	141.7	150.2
	Cube	51	142.4	7.9	0.0557	134.1	150.8
	Cylinder	102	139.9	2.8	0.0199	137.0	142.8
	Cylinder	76	137.8	4.0	0.0293	133.6	142.0
	Cylinder	51	117.0	11.5	0.0985	104.9	129.1
QW	Cube	100	139.0	1.6	0.0116	137.3	140.7
	Cube	70.7	141.9	2.9	0.0202	138.9	144.9
	Cube	51	139.7	2.2	0.0158	137.4	142.0
	Cylinder	102	138.0	2.2	0.0158	135.7	140.2
	Cylinder	76	136.6	2.8	0.0204	133.7	139.5
	Cylinder	51	113.8	4.4	0.0391	109.1	118.4
QF	Cube	100	120.2	2.6	0.0215	117.4	122.9
	Cube	70.7	120.8	3.3	0.0275	117.3	124.3
	Cube	51	119.4	2.9	0.0243	116.4	122.5
	Cylinder	102	112.5	1.7	0.0148	110.7	114.2
	Cylinder	76	105.9	2.8	0.0260	103.0	108.8
	Cylinder	51	95.9	5.3	0.0554	90.4	101.5

Table 3—Fiber-reinforced cylinder and cube test results (cont.)

Batch	Type	Size, mm	Compressive strength			95% confidence	
			Average, MPa	Standard deviation, MPa	Coefficient of variation	Lower, MPa	Upper, MPa
QG	Cube	100	105.0	3.1	0.0293	101.7	108.2
	Cube	70.7	109.5	2.4	0.0220	107.0	112.1
	Cube	51	107.7	1.7	0.0156	105.9	109.4
	Cylinder	102	97.6	2.6	0.0267	94.9	100.3
	Cylinder	76	94.7	2.9	0.0303	91.7	97.7
	Cylinder	51	88.5	4.3	0.0487	83.9	93.0
QX	Cube	100	84.2	1.7	0.0198	82.4	85.9
	Cube	70.7	86.4	2.4	0.0281	83.8	88.9
	Cube	51	82.4	0.9	0.0104	81.5	83.3
	Cylinder	102	79.8	1.0	0.0125	78.8	80.9
	Cylinder	76	78.2	1.4	0.0182	76.7	79.7
	Cylinder	51	73.2	1.9	0.0258	71.2	75.2

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

Table 4—Non-fiber-reinforced cylinder and cube test results

Batch	Type	Size. mm	Compressive strength			95% confidence	
			Average, MPa	Standard deviation, MPa	Coefficient of variation	Lower, MPa	Upper, MPa
QR	Cube	100	155.2	4.3	0.0396	105.1	114.3
	Cube	70.7	166.6	4.7	0.0304	150.3	160.2
	Cube	51	169.5	10.2	0.0611	155.9	177.3
	Cylinder	102	170.3	4.9	0.0290	165.1	175.4
	Cylinder	76	157.0	10.9	0.0692	145.6	168.4
	Cylinder	51	142.3	18.9	0.1328	118.8	165.8
QS	Cube	100	148.4	9.6	0.0569	159.4	179.6
	Cube	70.7	154.4	3.1	0.0207	145.2	151.7
	Cube	51	143.0	7.8	0.0507	146.1	162.6
	Cylinder	102	143.3	15.0	0.1046	127.6	159.1
	Cylinder	76	148.9	5.1	0.0344	143.6	154.3
	Cylinder	51	130.2	13.1	0.1009	116.4	144.0
QQ	Cube	100	116.9	2.2	0.0158	137.4	142.0
	Cube	70.7	119.4	3.1	0.0268	113.6	120.2
	Cube	51	109.7	3.5	0.0294	115.7	123.1
	Cylinder	102	119.8	2.7	0.0226	116.9	122.6
	Cylinder	76	117.9	5.2	0.0442	112.4	123.4
	Cylinder	51	90.2	17.2	0.1906	72.1	108.2

Note: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

All supplemental curing conditions were initiated within 30 hours of casting.

All compression tests were completed in a 4450 kN (1000 kip) compression testing machine. The cylinders were tested according to ASTM C39, except that the initial rate of load application was increased to 1.0 MPa/second (150 psi/second). The cubes were tested according to ASTM C109 with the same load rate modification. In all cases except one, six strength results were obtained for each specimen type from each batch of cylinders and cubes. The exception was the 51 mm (2 in.) cylinders in Batch QR, which only had five strength results.

TEST RESULTS AND ANALYSIS

Compressive strength results

The compressive strength results from the 503 cylinders and cubes tested in the study are presented in Tables 3 and 4. The results from the 11 batches containing fiber reinforcement are in Table 3, whereas the other three batches are in Table 4. The results from all 14 batches are presented graphically in Fig. 1. The batches have been arranged in this figure according to their compressive strength, with the average and the upper and lower 95% confidence interval of the compressive strength for each specimen type being shown. The compressive strengths covered (as observed from tests of 102 mm [4 in.] cylinders) ranged from 80 to 200 MPa (11.6 to 29.0 ksi).

A number of observations can be made based on these compressive strength results. First, the 70.7 and 51 mm (2.78 and 2 in.) cubes tend to show similar strengths with all of their confidence intervals overlapping, and their strengths tend to be at or above those exhibited by the other specimen types. Second, the 102 and 76 mm (4 and 3 in.) cylinders also tend to show similar strengths with all except one of their confidence intervals overlapping. Finally, the 51 mm (2 in.) cylinders tend to show similar or lower strengths as compared with all other specimen types.

The coefficient of variation information presented in Tables 3 and 4 and displayed in Fig. 2 are indicative of the dispersion that was observed in the test results. The coefficients

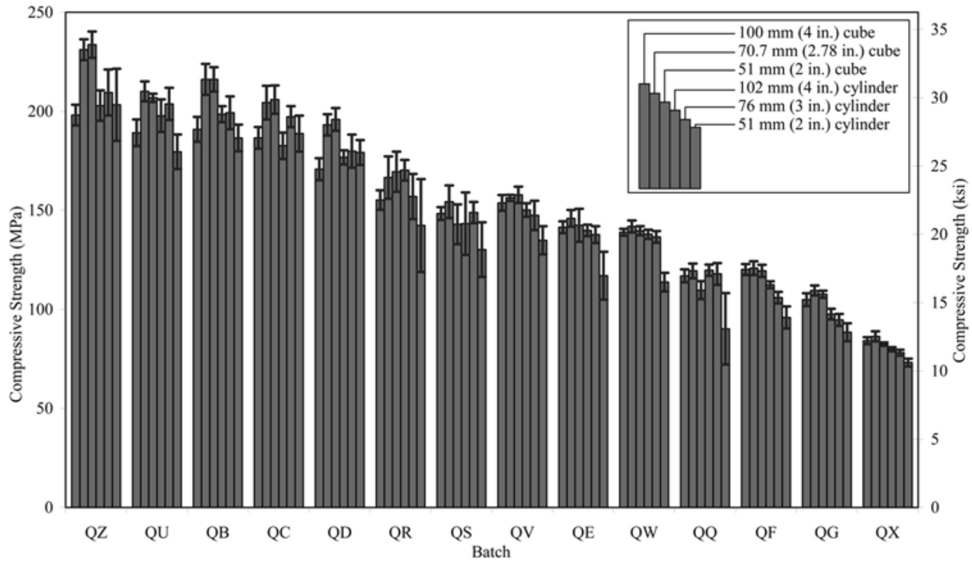

Fig. 1—Compressive strength of cylinders and cubes tested in this study.

Table 5—Coefficients for conversion of compressive strength results

Tested \ Desired	76 mm diameter cylinder	102 mm diameter cylinder
100 mm cube	Multiply by 1.00 (R^2 = 0.9672)	Multiply by 1.00 (R^2 = 0.9791)
70.7 mm cube	Multiply by 0.94 (R^2 = 0.9857)	Multiply by 0.93 (R^2 = 0.9694)
51 mm cube	Multiply by 0.96 (R^2 = 0.9541)	Multiply by 0.96 (R^2 = 0.9472)
102 mm cylinder	Multiply by 1.01 (R^2 = 0.9853)	—
76 mm cylinder	—	Multiply by 0.99 (R^2 = 0.9839)
51 mm cylinder	Multiply by 1.08 (R^2 = 0.9645)	Multiply by 1.07 (R^2 = 0.9360)

Note: 1 in. = 25.4 mm.

of variation from similar tests conducted in both Graybeal[16] and Ahlborn and Kollmorgen[17] are also presented in the figure. ASTM C39 indicates that the expected coefficient of variation for 100 mm (4 in.) cylinders tested at a single laboratory is 3.2%. Forty percent of specimen sets tested in this program displayed coefficients of variation above 3.2%. From the largest to smallest dimension, the median coefficients of variation for the cylinder sets tested in the three studies were 2.7, 3.8, and 5.5%. For the three sets of cubes, the values were 2.8, 2.8, and 3.3%. Cylinders in general, and 51 mm (2 in.) diameter cylinders in particular, make up a larger percentage of the specimen sets with higher coefficients of variation. Also, the results from batches that did not contain fiber reinforcement tended to display higher coefficients of variation.

Relationships between strengths observed

The test results presented previously demonstrate that, with the possible exception of the 51 mm (2 in.) cylinder specimens, these six specimen types tend to relate similar compressive strength results for individual batches of UHPFRC. As the 76 and 102 mm (3 and 4 in.) diameter cylinders are frequently used to relate the compressive

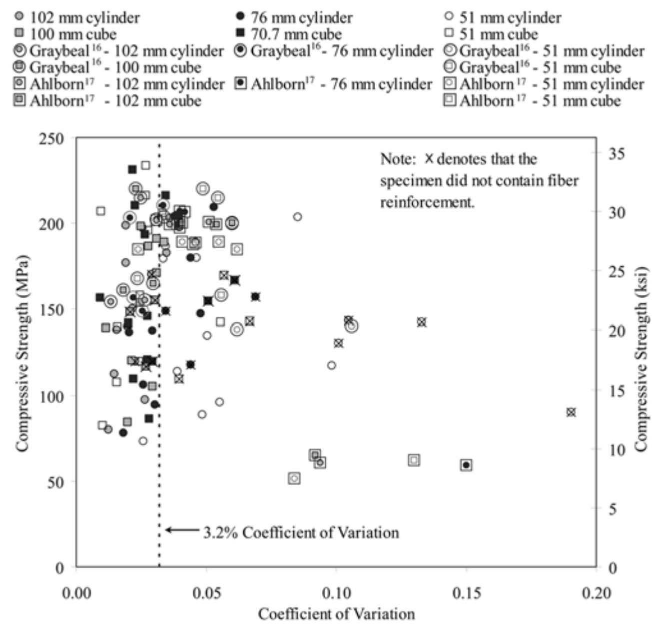

Fig. 2—Coefficient of variation results. (Note: 1 mm = 0.039 in.)

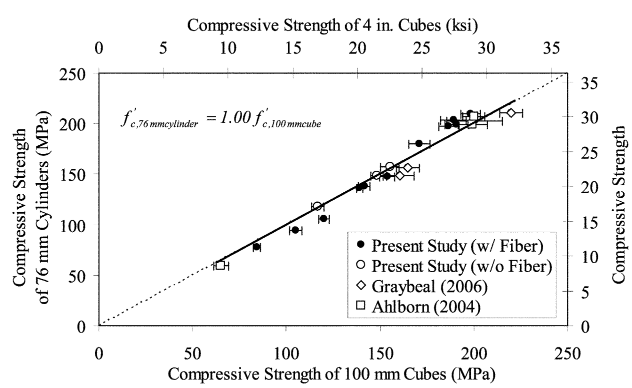

Fig. 3—Comparison of 100 mm (4 in.) cube and 76 mm (3 in.) cylinder results.

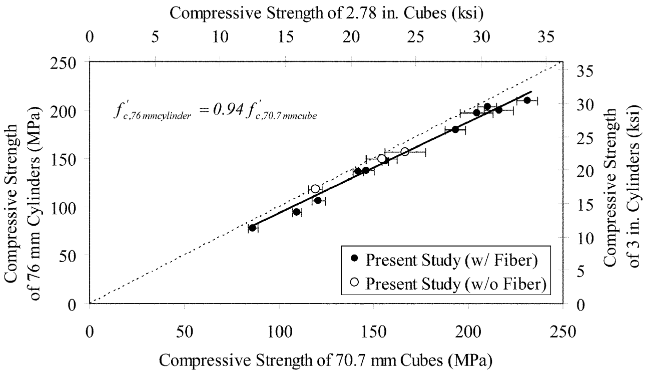

Fig. 4—Comparison of 70.7 mm (2.78 in.) cube and 76 mm (3 in.) cylinder results.

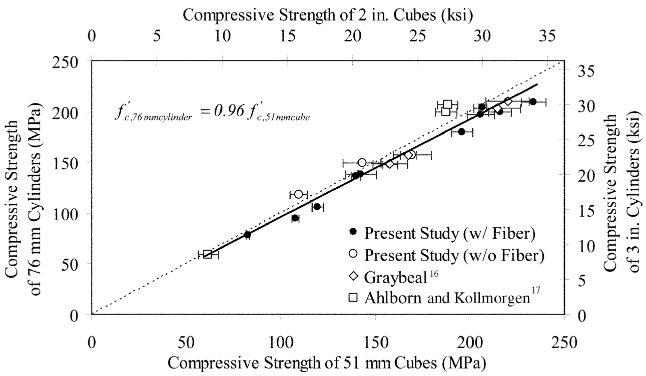

Fig. 5—Comparison of 51 mm (2 in.) cube and 76 mm (3 in.) cylinder results.

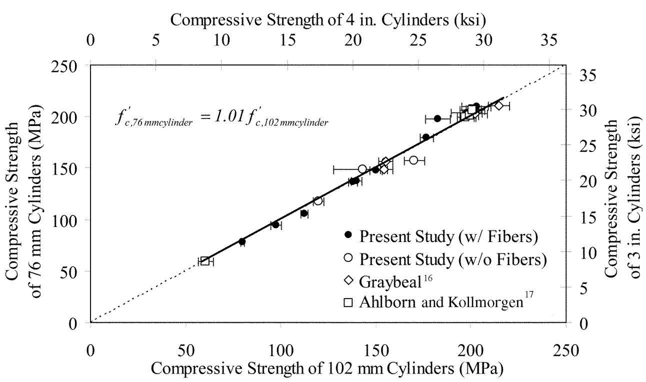

Fig. 6—Comparison of 102 mm (4 in.) cylinder and 76 mm (3 in.) cylinder results.

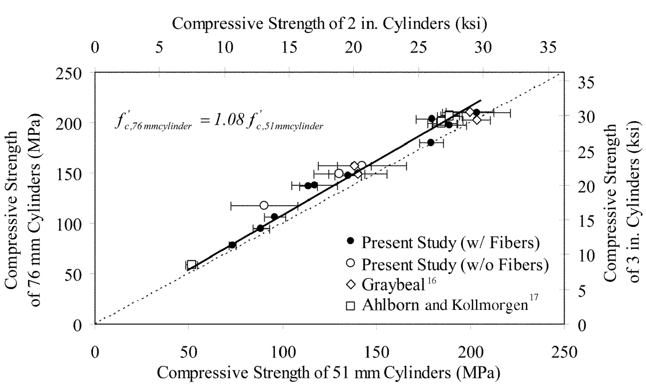

Fig. 7—Comparison of 51 mm (2 in.) cylinder and 76 mm (3 in.) cylinder results.

strength of concretes in the 140 to 200 MPa (20 to 30 ksi) range, these types of specimens were used as a references to which the compressive strength results of the specimen types were compared. Figures 3 through 7 plot the results of this study along with the results obtained in Graybeal[16] and Ahlborn and Kollmorgen[17] as compared with the 76 mm (3 in.) cylinders. The 95% confidence interval is shown for each specimen set, and the nonfiber reinforced specimens from the present study are distinguished from the remainder of the test results.

In the five plots, the least-squared best-fit line for the relationship between the compressive strength of the 102 mm (4 in.) cylinders ($f_c'{}_{,102\text{ mm cylinder}}$), the 51 mm (2 in.) cylinders ($f_c'{}_{,51\text{ mm cylinder}}$), the 102 mm (4 in.) cubes ($f_c'{}_{,100\text{ mm cube}}$), the 70.7 mm (2.78 in.) cubes ($f_c'{}_{,70.7\text{ mm cube}}$), and the 51 mm (2 in.) cubes ($f_c'{}_{,51\text{ mm cube}}$) and the compressive strength of the 76 mm (3 in.) cylinders ($f_c'{}_{,76\text{ mm cylinder}}$) is displayed. These least-squares fit lines were forced through the origin and are only displayed over the range of data for which they were calculated. The data from all three studies was included in the linear estimation process.

Table 5 presents the least-squares fit linear estimation of the conversion coefficients for relating strengths to the two cylinder diameters. The R^2 values are also presented. These results demonstrate that the 102 mm (4 in.) diameter cylinders, the 76 mm (3 in.) diameter cylinders, and the 102 mm (4 in.) cubes exhibit similar strengths and reasonable correlations. The highest correlation is exhibited by the relationship between the 70.7 mm (2.78 in.) cubes and the 76 mm (3 in.) cylinders, where a factor of 0.94 converts the earlier into the latter. Finally, the 51 mm (2 in.) cylinders and cubes both exhibit lesser correlations.

CONCLUSIONS

Based on the results of this experimental investigation of the compressive strength exhibited by various size cylinders and cubes, the following conclusions are drawn:

1. The 102 mm (4 in.) diameter cylinders, 76 mm (3 in.) diameter cylinders, and 100 mm (4 in.) cubes are acceptable and interchangeable test specimens for the determination of the compressive strength of UHPFRC;

2. The 70.7 mm (2.78 in.) cube is an acceptable alternative specimen type for determination of UHPFRC compressive strength in situations where testing machine capacity and/or cylinder end preparation equipment limitations are encountered. A factor of 0.96 should be applied to convert the cube strength result into an equivalent 76 mm (3 in.) diameter cylinder result;

3. The 51 mm (2 in.) cylinders and cubes exhibit the greatest strength variations and least correlation when compared with 76 and 102 mm (3 and 4 in.) diameter cylinder strength results. In particular, the 51 mm (2 in.) cylinders exhibit a significantly increased coefficient of variation; and

4. The exclusion of the fiber reinforcement from the mixture design of UHPFRC may result in an increase in the coefficient of variation of the compressive strength results.

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NOTATION

$f_c'{}_{,51\text{ mm cube}}$ = compressive strength of 51 mm (2 in.) cube
$f_c'{}_{,70.7\text{ mm cube}}$ = compressive strength of 70.7 mm (2.78 in.) cube
$f_c'{}_{,100\text{ mm cube}}$ = compressive strength of 100 mm (4 in.) cube
$f_c'{}_{,51\text{ mm cylinder}}$ = compressive strength of 51 mm (2 in.) cylinder
$f_c'{}_{,76\text{ mm cylinder}}$ = compressive strength of 76 mm (3 in.) cylinder
$f_c'{}_{,102\text{ mm cylinder}}$ = compressive strength of 102 mm (4 in.) cylinder

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