Effect of Size and Shape of Test Specimen on Compressive Strength of Concrete

by Subramanian Narayanan

National codes and specifications in North America, France, Japan, Australia, and New Zealand define cylinders as standard specimens for compressive strength testing of concrete, whereas much of the remainder of Europe and Asia relies on cube specimens. Per EN 206:2013, the characteristic compressive strength at the age of 28 days for normal strength concrete (NSC) is based on cylinders or cubes with 150 mm (6 in.) minimum dimensions.[1] However, retaining these specimen sizes as a standard for high-strength concrete (HSC) beyond 75 MPa (10,880 psi) and ultra-high-performance concrete (UHPC) may cause problems.

Two primary issues arise when using standard compression test machines to test HSC or UHPC: 1) the capacity of the testing machine may be insufficient; and 2) the ends of cylinders can require special preparation. In regard to the first issue, if the designed concrete strength is 100 MPa (14,500 psi), the maximum force that can be applied by a standard machine (about 2000 kN [449,620 lb]) may not be sufficient to crush a 150 x 300 mm (6 x 12 in.) cylinder or a 150 mm cube. Hence, smaller cylinders or cubes may be required. However, using test specimens with different shapes and sizes other than the standard sizes specified in the codes may lead to difficulty in correlation of compressive strength of concrete. Multi-axial compression stress-states vary with the slenderness of the test specimen,[2] and many researchers (refer to the following section) have found that cube specimens with smaller dimensions (for example, 100 mm [4 in.]) have higher strengths than specimens with larger dimensions (for example, 150 mm).

The second issue can be resolved using cube specimens in lieu of buying expensive grinding equipment to prepare cylinder ends. The combination of these solutions (using small cubes), however, is not considered standard practice in the concrete industry and may raise concerns about the accuracy and reliability of the test results.

Previous Research

Many studies have been conducted on this topic in the past 100 years. As early as 1925, Gonnerman[3] investigated the relationship between various cylinder and cube sizes on the compressive strength of concrete. For standard concrete mixtures, at normal compressive strength levels, it was generally assumed that cubes will have a higher compressive strength than cylinders (up to 25%), but the difference will decrease with increasing strength levels.

There has been a series of research efforts in the past 40 years focused on such issues. In 1987, Nasser and Al-Manaseer[4] and Nasser and Kenyon in 1984[5] suggested that the 75 mm (3 in.) diameter cylinder results could be accepted as a standard compressive strength specimen. In 1994, Day[6] compiled research results from 22 separate studies and performed statistical analyses on the relationship between 75, 100, and 150 mm cylinders. In 2000, Issa et al.[7] investigated the effect of 50 to 150 mm (2 to 6 in.) cylinders on the compressive strength of concrete. In 1994, Aïtcin et al.[8] investigated the effects of size and curing on cylinder compressive strength of NSCs and HSCs up to 120 MPa (17,400 psi). In 2002, Mansur and Islam[9] investigated the relationship between 100 mm cylinders and 150 mm cubes and compressive strengths up to 100 MPa. The conclusions of these investigations are generally similar. As the specimen size increases, its compressive strength decreases. The strength of smaller cylinders or cubes was slightly higher than the strength expressed by the 150 mm diameter cylinder, and the strength differences decreased at higher compressive strengths. Also, the variation in the compressive strength increased with decreasing the specimen size. In 2008, Graybeal and Davis[10] conducted compressive strength tests on 51, 75, and 100 mm cylinders and 51, 70.7, and 100 mm cubes of ultra-high-performance fiber-reinforced concrete (UHPFRC) with strength ranging from 80 to 200 MPa

(11,600 and 29,000 psi). They found that the 76 mm cylinder, as well as the 70.7 and 100 mm cubes, could be acceptable alternatives to the standard 100 mm cylinder specimens. They recommended the 70.7 mm cube specimens for situations where machine capacity, cylinder end preparation, or both are of concern.

A number of empirical models have also been developed from the test results, such as statistical size effect, fractal size effect, energetic size effect, and critical phase transition. A detailed study of previous research on these empirical models is presented by Talaat et al.[11]

Cylinder versus Cube Strength

The main difference between cylinder and cube testing procedures is the need for capping cylinders. The ends of cast cylinders are usually not plane or sufficiently parallel to mate properly with the platens of compression testing machines, and hence are capped with sulfur, neoprene, or other suitable material for proper distribution of the applied load. Cubes, however, are not capped but cast in rigid molds with sides that are plane and parallel. When tested, they are flipped on their sides so that the machine platens mate properly with the cube surfaces. The factors affecting the cylinder/cube strength ratio are: 1) casting, curing, and testing procedures; 2) geometry of specimens; 3) strength levels; 4) direction of loading and characteristics of the machine; and 5) aggregate grading.[12]

Cylinders are considered to give a greater uniformity of results because their failure is less affected by the end restraint of the platens of the testing machine on the specimen. In addition, their strength is less influenced by the properties of the coarse aggregate used in the mixture; and the stress distribution on horizontal planes in a cylinder is found to be more uniform than on cubes. Due to this reason, and because the standard cylinders have *h*/*d* of 2, the compressive strengths predicted by cylinders are more reliable than cubes. However, the strength of a cylinder is generally lower than that of a cube.[3] The higher cube strength is usually attributed to having an overlapped restrained zone in cubes under uniaxial compression (resulting in multi-axial stresses throughout the cube), while the cylinders have an unrestrained zone of 0.268*d* in the middle portion.[12] Changing aggregate grading affects cube strength more than cylinder strength, and increasing aggregate coarseness decreases the cylinder/cube strength ratio.[12]

The standard cylinder strength f_c' is usually converted to standard cube strength f_{ck} by using the relation $f_c' = 0.8 f_{ck}$. In 1966, Neville[13] developed a relationship between the strength to the volume of a specimen (V), lateral dimension (d), and height to lateral dimension ratio (h/d), which agreed well with the test data, up to 600 mm (24 in.) diameter. According to Neville, the coefficient K to convert cylinder strength to cube strength is

$$K = 0.76 + 0.2\log\left(\frac{f_c'}{20}\right) \tag{1}$$

The conversion of cylinder to cube strength as per Eurocode 2[14] is compared with Eq. (1) in Table 1.

The cubic compressive strength of several specimens tested by Pacheco et al.[15] is compared in Fig. 1 with the ratio of cylinder/cube strength suggested by EN206[1]/Eurocode 2.[14] From this figure, a significant scatter between the cylinder/cube strength ratio (K) of EN206[1]/Eurocode 2[14] and actual

Table 1:
Conversion of cylinder to cube strength as per Eurocode 2[14] and Neville's equation[13]

Characteristic cylinder strength ($f_{ck,cyl}$), N/mm^2	Characteristic cube strength ($f_{ck,cube}$), N/mm^2	Ratio of cylinder/cube strength (K)	
		Eurocode 2	Eq. (1)
16	20	0.80	0.74
20	25	0.80	0.76
25	30	0.83	0.78
30	37	0.81	0.80
35	45	0.78	0.81
40	50	0.80	0.82
45	55	0.82	0.83
50	60	0.83	0.84
55	67	0.82	0.85
60	75	0.80	0.86
70	85	0.82	0.87
80	95	0.84	0.88
90	105	0.86	0.89
100	115	0.87	0.90

Note: 1 N/mm^2 = 145 psi

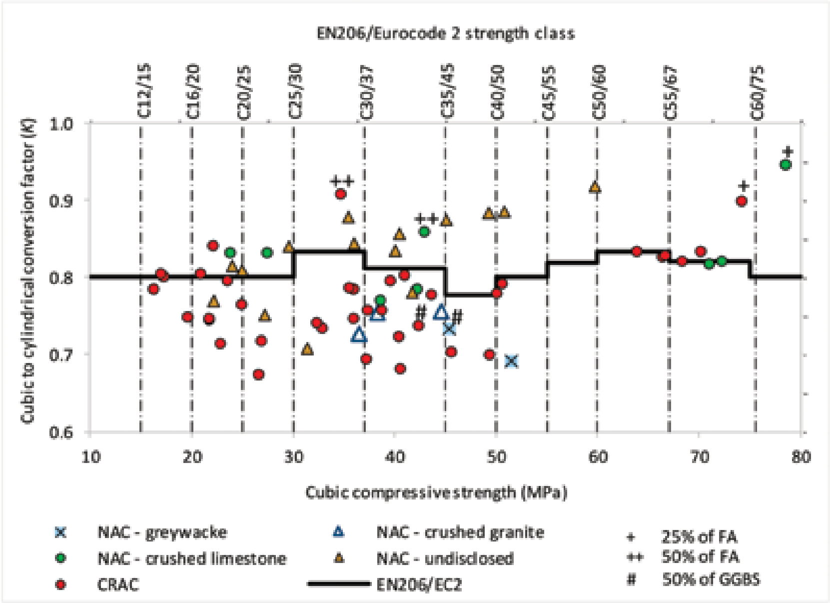

Fig. 1: Comparison of cylinder/cube strength factor with cube strength and EN206[1]/Eurocode 2[14] suggested conversion (from Reference 15)

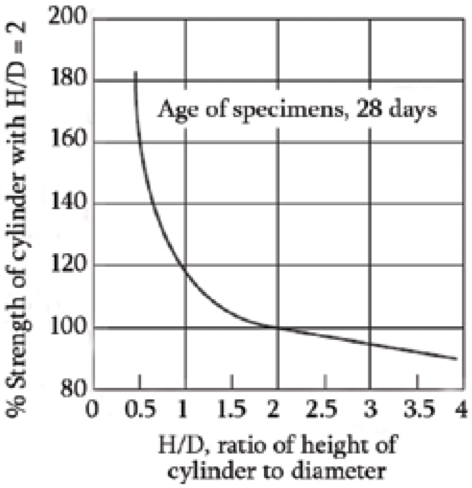

Fig. 2: Effect of height to diameter ratio (*h*/*d*) on the strength of cylinders (from Reference 12)

data of both recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) can be seen. From Fig. 1, it can be also observed that, when the compressive strength is below 50 MPa (7250 psi), the conversion factors of EN206[1]/Eurocode 2[14] overestimate the strength of RAC cylinders, which may lead to unsafe designs. This means that a specific factor for RAC conversions is necessary. Pacheco et al.[15] found that incorporation of coarse recycled aggregate (CRA) sourced from concrete waste decreases *K*; the values of *K* for NAC were in the range of 0.81 to 0.92, while most of RAC varied between 0.71 and 0.84.

Difficulties of Testing High-Strength Specimen and Codes of Practices

From a practical standpoint, the compressive strength testing of 150 mm cylinders of M80 to M200 (11,600 to 29,000 psi) concretes may require both a 4500 kN (101,165 lb) compression machine and grinding of the ends of a cylinder, thus making the testing a specialized task, which is not possible in all testing laboratories.[10]

According to Graybeal and Davis,[10] only two countries have design guidelines pertaining to the testing of HSC using smaller-size specimens. The French specification[16] 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[17] suggests the use of 100 mm diameter cylinders. IS 1199 (Part 5):2018[18] suggests that either cube (of size 150 mm) or cylinder specimens (150 mm in diameter and 300 mm in length) can be used for determining the compressive strength. IS 1199 (Part 5)[18] allows 100 mm cubes also to be tested as an alternative, provided the largest nominal size of aggregates does not exceed 20 mm (3/4 in.). In addition, smaller cylinder test specimens are also allowed, provided the cylinders have a minimum diameter to maximum nominal size of aggregate ratio of four. ACI 318M-19, Provision 26.12.1.1,[19] permits 100 x 200 mm (4 x 8 in.) or 150 x 300 mm test cylinders. As stated in the Code, the average difference between test results obtained by the two specimen sizes is not considered to be significant in design.[20]

Conversion Factors for Different Shapes and Different Concretes

The pronounced effect of *h*/*d* and the cross-sectional dimension of test specimens on the compressive strength have been observed by several researchers. The difference in compressive strength of different sizes of specimens may be due to several factors such as St. Venant's effect, size effect, or lateral restraint effect due to the platen of testing machines. The size effect is more predominant when small-scale specimens are used. The general relationship observed between *h*/*d* and strength is shown in Fig. 2. It can be clearly seen that the strength ratio is more sensitive to *h*/*d* for $h/d < 1.5$ than $h/d > 1.5$.[12]

When *h*/*d* of cylinders is less than 2.0, IS 516:1959[21] suggests a correction factor shown in Fig. 3. Standard cubes have been found to have higher compressive strength than standard cylinders with *h*/*d* of 2.0. The ratio of standard cylinder strength and standard cube strength is about 0.8 to 0.95; higher ratio is applicable for HSC. Similarly, 100 x 200 mm cylinders exhibit 2 to 10% higher strengths than 150 x 300 mm (6 x 12 in.) cylinders; the difference is less for higher strength concrete.[10]

The standard size of specimen for testing the compressive strength of concrete is a 150 x 300 mm cylinder. When such cylinders with *h*/*d* of 2 and varying diameters were tested in compression, it was found that larger diameter cylinders had lower strength, as shown in Fig. 4. Thus, the average strength of 50 x 100 mm and 75 x 150 mm cylindrical specimens were 108 and 106%, respectively, when compared to the standard size specimens. When the diameter was increased beyond 450 mm (18 in.), a much smaller reduction in strength was observed.

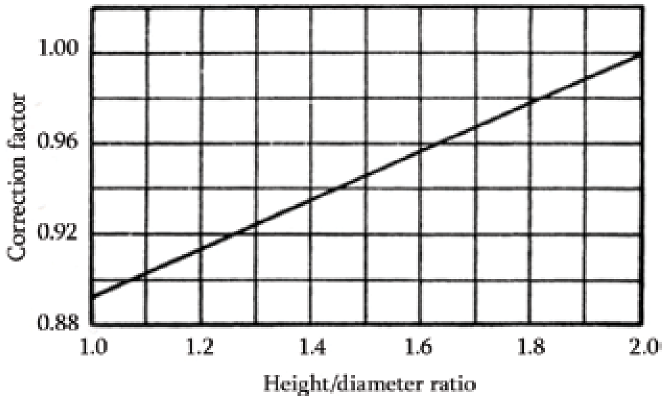

Fig. 3: Correction factor for *h*/*d* of cylinder per IS 516:1959[21]

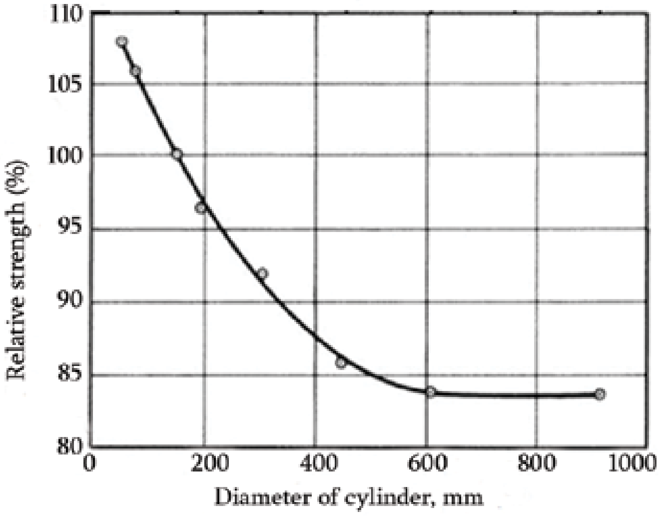

Fig. 4: Influence of the specimen diameter on concrete strength when *h*/*d* = 2 (from Reference 22) (Note: 1 mm = 0.04 in.)

For NSC and HSC, appropriate conversion factors have been established by several researchers.[2,23,24] Thus, the results obtained from different size specimens can be related to a reference cylinder with *h*/*d* = 300/150 (in mm) and can be used as the basis for structural design (per EN 1992-1-1:2004[14]). As shown in Fig. 5, NSC cylinder with *h*/*d* = 300/150 (in mm) typically reaches only about 82% of the compressive strength of a 150 mm cube and only about 75% of the compressive strength of a 100 mm cube. However, these factors increase for HSC, and hence the difference in strength is smaller than that of NSC.

An investigation by Malaikah[25] on the shape and size effect on compressive strength of HSC proposed the following conversion factors: 0.8 for a 150 x 300 mm cylinder versus a 150 mm cube, 0.93 for a 100 x 200 mm cylinder versus a 150 mm cube, and 0.866 for a 150 x 300 cylinder versus a 100 x 200 mm cylinder.

Graybeal and Davis[10] evaluated 14 series of compression tests on HSC and UHPC mixtures, using premixtures without coarse aggregate and with compressive strengths ranging between 80 and 200 MPa. Each series included three sizes of cylinders (*d* = 51, 76, and 102 mm) with *h*/*d* = 2 and three sizes of cubes (51, 70.7, and 100 mm). Most of the specimens were heat-treated, and some were cured in air. Comparison of mean compressive strengths obtained from cylinders with *d* = 102 mm and 100 mm cubes resulted in conversion factors for cylinder-to-cube strength ratio of 1.00 for the UHPC mixtures (Table 2). From this table, it can be seen that in most cases, the compressive strength obtained from cylinders was higher than the compressive strength obtained from cubes.

Wall Effect

When the maximum size of coarse aggregate in concrete is large with respect to the diameter of a cylinder or the size of a cube, the packing of coarse aggregate in the boundary layer between the wall of the mold and the concrete becomes less uniform. The concrete cannot be compacted sufficiently in these regions. It results in an increased quantity of mortar to fill the space between the coarse aggregate particles and the

Table 2:
Conversion coefficients for HSC/UHPC specimens of different sizes (from Reference 10)

Tested specimens		Desired cylinder diameters	
		76 mm	102 mm
Cubes	100 mm	× 1.00 (R^2 = 0.9672)	× 1.00 (R^2 = 0.9791)
	70.7 mm	× 0.94 (R^2 = 0.9857)	× 0.93 (R^2 = 0.9694)
	51 mm	× 0.96 (R^2 = 0.9541)	× 0.96 (R^2 = 0.9472)
Cylinders	102 mm diameter	× 1.01 (R^2 = 0.9853)	—
	76 mm diameter	—	× 0.99 (R^2 = 0.9839)
	51 mm diameter	× 1.08 (R^2 = 0.9645)	× 1.07 (R^2 = 0.9360)

Note: 1 mm = 0.04 in.

wall of the mold. This phenomenon is known as the wall effect. To reduce this wall effect, ASTM C192/C192M, Section 6.4,[26] stipulates that the diameter of a test cylinder should be at least three times the nominal maximum size of the aggregate. The British Standard 1881: Part 108[27] suggests using 100 mm nominal size cubes for concrete with aggregates having a nominal size not exceeding 20 mm (3/4 in.), and 150 mm cubes for concretes with aggregates not exceeding 40 mm (1-1/2 in.).

Turkel and Ozkul[28] found that an optimum aggregate size exists that makes the size effect minimum; for NSC and HSC, they found that the size effect is minimum for 50 to 200 mm cubes for a 22 mm (3/4 in.) aggregate size. Carpinteri et al.[29] suggested that to minimize size effect, the codes should stipulate that the compressive strength should be conducted on specimens with a dimension greater than $10d_{max}$, where d_{max} is the maximum size of aggregates used.

Size Effect Law

Bažant and Planas[30] proposed the following classical size effect law (SEL) based on fracture mechanics

$$\sigma_N = \frac{Bf_t'}{\sqrt{1+\dfrac{d}{d_0}}} \tag{2}$$

where σ_N is the compressive strength, B and d_0 are constants to be determined experimentally, f_t' is the strength parameter (taken as tensile strength), and d is the characteristic dimension of the structure (size of specimen). As per this size effect, when the size of the specimen is increased, the compressive strength of the specimens of the same mixture design decreases. There is a major problem with Eq. (2) though, as it predicts a severe strength reduction for larger specimens, which contradicts the actual test results. Another issue is that it's only applicable for structures having a notch or a crack initially.

Based on statistical analyses, Kim and Yi[31] developed the following size effect equation to predict the compressive strength of cylinder specimens, without considering the effect of maximum aggregate size

$$f_c = \frac{0.4f_c'}{\sqrt{1+(h-d)/50}} + 0.8f_c' \tag{3}$$

where f_c is the strength of a nonstandard cylinder and f_c' is the strength of a standard cylinder both in MPa, and h is the height of a cylinder and d is the diameter of a cylinder both in mm. The proposed Eq. (3) showed good agreement with the existing test results for concrete cylinders and compared well with the results shown in Fig. 2.

It has been found that for cubes, the classical SEL expression may be modified to

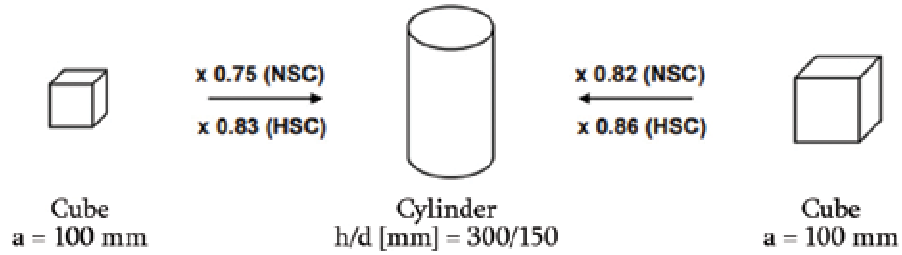

Fig. 5: Conversion factors for compressive strength of NSC and HSC for different specimen shapes and sizes (from Reference 24) (Note: 100 mm = 4 in.)

$$f_{cu} = f_{ck}\sqrt{\frac{L}{L+L_0}} \tag{4}$$

where f_{cu} is the strength of a nonstandard cube and f_{ck} is the strength of a standard cube both in MPa, and L is the size of a nonstandard cube and L_0 is an empirically derived constant both in mm. The value of L_0 has been found from experiments to be equal to 20 mm.

Conclusions

The compressive strength of concrete is an important parameter used in structural design, as all other strengths are expressed in terms of the compressive strength. National codes suggest determining the compressive strength based on tests conducted on standard 150 x 300 mm cylinders or 150 mm cubes. However, these codes do not provide any correlation between the cube strength and the cylinder strength, although the cube strength is normally assumed to be 1.25 times the cylinder strength. Experiments have shown that the cylinder-to-cube strength ratio varies with the level of strength of concrete, with the difference narrowing for HSC. The cylinder-to-cube strength ratio suggested by Eurocode 2[14] is not in agreement with test data, as there is a large scatter in the results.

Keeping the previously mentioned specimen sizes as standard for HSC or UHPC may cause problems due to the higher ultimate loads required to break these cubes/cylinders and the limited capacity of available testing machines. Hence, smaller size cubes/cylinders are often used. Again, the correlation between these test results with the standard size cubes/cylinders are required as the values presented in the codes as compressive strength refer to the standard cube/cylinder sizes.

Based on the results of experimental investigations by various researchers on the compressive strength of various sizes of cylinders and cubes, the following conclusions can be drawn:

- The size effect is not constant for any specimen geometry. The size effect is more pronounced in cubic specimens than in cylindrical ones. It was found that the standard deviation of the strength decreased as the diameter increased. The strength in cylinders was observed to approach a constant value beyond 600 mm (27.5 in.);
- The strength ratio is more sensitive to h/d for $h/d < 1.5$ than for $h/d > 1.5$. The influence of the specimen slenderness

decreases significantly with increasing concrete compressive strength. For UHPC, the ratio of compressive strength between cylinder and cube is close to 1.0.[10] Maximum aggregate size does not influence the ratio of compressive strength for UHPC.[10] When keeping the slenderness constant, compressive strength of NSC, HSC, and UHPC changes only marginally for different specimen sizes;

- There is no definite relation between the compressive strengths of various specimen shapes; only empirical conversions exist. Using such conversion factors, one must consider various parameters (including strength level, concrete type, aggregate size/gradation, capping, mold material, curing conditions, consolidation methods, and specimen age) affecting these conversions to choose the most suitable factor[11];
- Cylinders with 100 mm and 76 mm diameters and cubes with 100 mm sides are acceptable and interchangeable test specimens for the determination of the compressive strength of UHPFRC[10]; and
- The size effect in HSC is not yet fully understood. Debate exists for whether the size effect is more pronounced in lower- or higher-strength concrete.[11]

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Selected for reader interest by the editors.

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Fig. 3 Factor de corrección para h/d del cilindro según IS 516:1959[21].

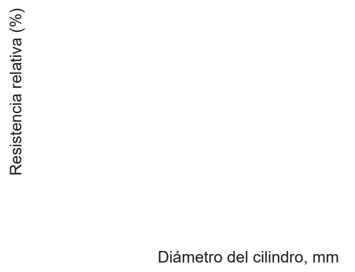

Fig. 4 Influencia del diámetro de la muestra en la resistencia del concreto cuando h/d = 2 (de la Referencia 22) (Nota: 1 mm = 0.04 pulg.).

Desde un punto de vista práctico, la prueba de resistencia a la compresión de probetas cilíndricas de 150 mm de concreto M80 a M200 (11,600 a 29,000 psi) puede requerir tanto una máquina de compresión de 4500 kN (101,165 lb) como un rectificado de los extremos del cilindro, lo que hace que la prueba sea una tarea especializada, que no es posible en todos los laboratorios de pruebas[10].

Según Graybeal y Davis[10], sólo dos países tienen directrices de diseño relativas a las pruebas de CAR utilizando probetas de menor tamaño. La especificación francesa[16] sugiere el uso de probetas cilíndricas de 70 o 110 mm (2.75 o 4.3 pulgadas) para determinar la resistencia a la compresión, mientras que la especificación japonesa[17] sugiere el uso de probetas cilíndricas de 100 mm de diámetro. IS 1199 (Parte 5):2018[18] sugiere que se pueden utilizar probetas cúbicas (de tamaño 150 mm) o cilíndricas (150 mm de diámetro y 300 mm de longitud) para determinar la resistencia a la compresión. IS 1199 (Parte 5)[18] permite que también se ensayen probetas cúbicas de 100 mm como alternativa, siempre que el tamaño nominal más grande de los agregados no supere los 20 mm (3/4 pulg.). Además, también se permiten probetas cilíndricas más pequeñas, siempre que las probetas cilíndricas tengan una proporción de agregado de cuatro entre el diámetro mínimo y el tamaño nominal máximo de agregado. ACI 318M-19, disposición 26.12.1.1[19], permite las probetas cilíndricas de 100 x 200 mm (4 x 8 pulgadas) o 150 x 300 mm. Como se establece en el Código, la diferencia promedio entre los resultados de las pruebas obtenidas con los dos tamaños de probetas no se considera significativa en el diseño[20].

Factores de conversión para diferentes formas y diferentes concretos

Varios investigadores han observado el efecto pronunciado de *h/d* y la dimensión de la sección transversal de las probetas sobre la resistencia a la compresión. La diferencia en la resistencia a la compresión de diferentes tamaños de probetas puede deberse a varios factores, como el efecto de St. Venant, el efecto de tamaño o el efecto de restricción lateral debido a la platina de las máquinas de ensayo. El efecto del tamaño es más predominante cuando se utilizan probetas de pequeña escala. La relación general observada entre *h/d* y la resistencia se muestra en la Fig. 2. Se puede ver claramente que la relación de resistencia es más sensible a *h/d* para *h/d* < 1.5 que *h/d* > 1.5[12].

Cuando *h/d* de las probetas cilíndricas es inferior a 2.0, la norma IS 516:195921 sugiere un factor de corrección que se muestra en la Fig. 3. Se ha descubierto que los cubos estándar tienen una mayor resistencia a la compresión que las probetas cilíndricas estándar con *h/d* de 2.0. La relación entre la resistencia del cilindro estándar y la resistencia del cubo estándar es de aproximadamente 0.8 a 0.95; se aplica una relación más alta para CAR. De manera similar, las probetas cilíndricas de 100 x 200 mm exhiben resistencias entre un 2 y un 10 % mayores que las probetas cilíndricas de 150 x 300 mm (6 x 12 pulg.); la diferencia es menor para el concreto de mayor resistencia[10].

El tamaño estándar de muestra para probar la resistencia a la compresión del concreto es un cilindro de 150 x 300 mm. Cuando se probaron en compresión las probetas cilíndricas con *h/d* de 2 y diámetros variables, se encontró que las probetas cilíndricas de mayor diámetro tenían menor resistencia, como se muestra en la Fig. 4. Por lo tanto, la resistencia promedio de 50 x 100 mm y 75 x 150 mm. Las probetas cilíndricas fueron 108 y 106%, respectivamente, en comparación con las probetas de tamaño estándar. Cuando el diámetro se aumentó más allá de 450 mm (18 pulgadas), se observó una reducción mucho menor en la resistencia.

Para CRN y CAR, varios investigadores han establecido factores de conversión apropiados[2,23,24]. Por lo tanto, los resultados obtenidos de probetas de diferentes tamaños pueden relacionarse con un cilindro de referencia con *h/d* = 300/150 (en mm) y pueden utilizarse como base para el diseño estructural (según EN 1992-1-1:2004[14]). Como se muestra en la Fig. 5, el cilindro CRN con *h/d* = 300/150 (en mm) normalmente alcanza sólo aproximadamente el 82% de la resistencia a la compresión de un cubo de 150 mm y sólo aproximadamente el 75% de la resistencia a la compresión de un cubo de 100 mm. Sin embargo, estos factores aumentan para CAR y, por lo tanto, la diferencia de resistencia es menor que la de CRN.

Una investigación realizada por Malaikah[25] sobre el efecto de la forma y el tamaño sobre la resistencia a la compresión del CAR propuso los siguientes factores de conversión: 0.8 para un cilindro de 150 x 300 mm versus un cubo de 150 mm, 0.93 para un cilindro de 100 x 200 mm versus un cubo de 150 mm, y 0.866 para un cilindro de 150 x 300 frente a un cilindro de 100 x 200 mm.

Graybeal y Davis[10] evaluaron 14 series de ensayos de compresión sobre mezclas de CAR y CUAD, utilizando premezclas sin agregado grueso y con resistencias a la compresión que oscilaban entre 80 y 200 MPa. Cada serie incluía tres tamaños de probetas cilíndricas (*d* = 51, 76 y 102 mm) con *h/d* = 2 y tres tamaños de probetas cúbicas (51, 70,7 y 100 mm). La mayoría de las probetas fueron tratadas térmicamente y algunas se curaron al aire. La comparación de las resistencias a la compresión medias obtenidas de probetas cilíndricas con *d* = 102 mm y cubos de 100 mm dio como resultado factores de conversión para la relación de resistencia cilindro-cubo de 1.00 para las mezclas de CUAD (Tabla 2). De esta tabla se puede ver que, en la mayoría de los casos, la resistencia a la compresión obtenida de las probetas cilíndricas fue mayor que la resistencia a la compresión obtenida de las cúbicas.

Tabla 2:
Coeficientes de conversión para probetas de CAR/CUAD de diferentes tamaños (de la Referencia 10)

Probetas ensayadas		Diámetros deseados del cilindro	
		76 mm	102 mm
Cubos	100 mm	× 1.00 ($R^2 = 0.9672$)	× 1.00 ($R^2 = 0.9791$)
	70.7 mm	× 0.94 ($R^2 = 0.9857$)	× 0.93 ($R^2 = 0.9694$)
	51 mm	× 0.96 ($R^2 = 0.9541$)	× 0.96 ($R^2 = 0.9472$)
Cilindros	102 mm diámetro	× 1.01 ($R^2 = 0.9853$)	—
	76 mm diámetro	—	× 0.99 ($R^2 = 0.9839$)
	51 mm diámetro	× 1.08 ($R^2 = 0.9645$)	× 1.07 ($R^2 = 0.9360$)

Nota: 1 mm = 0.04 in.

Efecto de Muro

Cuando el tamaño máximo del agregado grueso en el concreto es grande con respecto al diámetro de un cilindro o al tamaño de un cubo, el empaquetamiento del agregado grueso en la capa límite entre la pared del molde y el concreto se vuelve menos uniforme. En estas zonas el concreto no se puede compactar lo suficiente. Da como resultado una mayor cantidad de mortero para llenar el espacio entre las partículas de agregado grueso y la pared del molde. Este fenómeno se conoce como efecto pared. Para reducir este efecto de pared, ASTM C192/C192M, Sección 6.4[26], estipula que el diámetro de una probeta cilíndrica debe ser al menos tres veces el tamaño máximo nominal del agregado. La norma británica 1881: Parte 108[27] sugiere usar cubos de tamaño nominal de 100 mm para concreto con agregados que tengan un tamaño nominal que no exceda los 20 mm (3/4 pulg.), y cubos de 150 mm para concretos con agregados que no excedan los 40 mm (1-1 /2 pulg.).

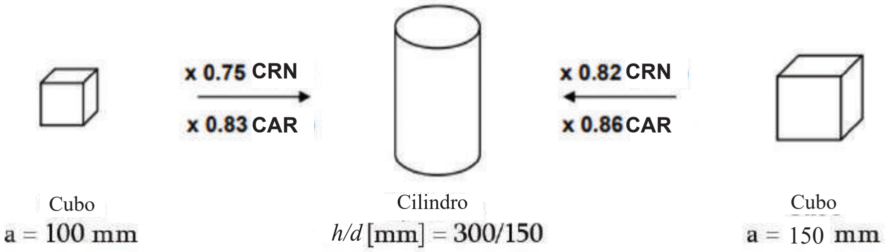

Fig. 5: Factores de conversión para la resistencia a la compresión de CRN y CAR para diferentes formas y tamaños de probetas (de la Referencia 24) (Nota: 100 mm = 4 pulg.).

Turkel y Ozkul[28] encontraron que existe un tamaño de agregado óptimo que hace que el efecto del tamaño sea mínimo; para CRN y CAR, encontraron que el efecto del tamaño es mínimo para cubos de 50 a 200 mm para un tamaño de agregado de 22 mm (3/4 pulg.). Carpinteri et al.[29] sugirieron que, para minimizar el efecto del tamaño, los códigos deberían estipular que la resistencia a la compresión debería realizarse en especímenes con una dimensión mayor que $10d_{max}$, donde d_{max} es el tamaño máximo de agregados utilizados.

Ley del efecto del tamaño

Bažant y Planas[30] propusieron la siguiente ley clásica del efecto del tamaño basada en la mecánica de fracturas

$$\sigma_N = \frac{Bf'_t}{\sqrt{1+\frac{d}{d_0}}} \qquad (2)$$

donde σ_N es la resistencia a la compresión, B y d_0 son constantes que se determinarán experimentalmente, f'_t es el parámetro de resistencia (tomado como resistencia a la tracción) y d es la dimensión característica de la estructura (tamaño de la muestra). Según este efecto de tamaño, cuando se aumenta el tamaño de la muestra, la resistencia a la compresión de las probetas del mismo diseño de mezcla disminuye. Hay un problema importante con la ecuación (2), ya que predice una severa reducción de la resistencia para probetas más grandes, lo que contradice los resultados reales de las pruebas. Otro problema es que sólo es aplicable a estructuras que inicialmente tienen una muesca o una grieta.

Con base en análisis estadísticos, Kim y Yi[31] desarrollaron la siguiente ecuación del efecto del tamaño para predecir la resistencia a la compresión de las probetas cilíndricas, sin considerar el efecto del tamaño máximo del agregado.

$$f_c = \frac{0.4f'_c}{\sqrt{1+(h-d)/50}} + 0.8f'_c \qquad (3)$$

donde f_c es la resistencia de un cilindro no estándar y f'_c es la resistencia de un cilindro estándar, ambos en MPa, y h es la altura de un cilindro y d es el diámetro de un cilindro, ambos en mm. La ecuación propuesta (3) mostró una buena concordancia con los resultados de las pruebas existentes para probetas cilíndricas de concreto y se comparó bien con los resultados mostrados en la Fig. 2.

Se ha descubierto que, para cubos, la expresión de la ley clásica del efecto del tamaño puede modificarse para

$$f_{cu} = f_{ck}\sqrt{\frac{L}{L+L_0}} \qquad (4)$$

donde fcu es la resistencia de un cubo no estándar y f_{ck} es la resistencia de un cubo estándar, ambas en MPa, y L es el tamaño de un cubo no estándar y L_0 es una constante derivada empíricamente, ambas en mm. Experimentalmente se ha demostrado que el valor de L_0 es igual a 20 mm.

Conclusiones

La resistencia a la compresión del concreto es un parámetro importante utilizado en el diseño estructural, ya que todas las demás resistencias se expresan en términos de resistencia a la compresión. Los códigos nacionales sugieren determinar la resistencia a la compresión basándose en pruebas realizadas en probetas cilíndricas estándar de 150 x 300 mm o cubos de 150 mm. Sin embargo, estos códigos no proporcionan ninguna correlación entre la resistencia del cubo y la resistencia del cilindro, aunque normalmente se supone que la resistencia del cubo es 1.25 veces la resistencia del cilindro. Los experimentos han demostrado que la relación de resistencia del cilindro al cubo varía con el nivel de resistencia del concreto, y la diferencia se reduce para el CAR. La relación de resistencia cilindro-cubo sugerida por el Eurocódigo 2[14] no concuerda con los datos de las pruebas, ya que hay una gran dispersión en los resultados.

Mantener los tamaños de muestra mencionados anteriormente como estándar para CAR o CUAD puede causar problemas debido a las mayores cargas finales requeridas para romper estas probetas cúbicas/cilíndricas y la capacidad limitada de las máquinas de prueba disponibles. Por lo tanto, a menudo se utilizan probetas cúbicas/cilíndricas de menor tamaño. Nuevamente, se requiere la correlación entre los resultados de estas pruebas con las probetas cúbicas/cilíndricas de tamaño estándar, ya que los valores presentados en los códigos como resistencia a la compresión se refieren a los tamaños de probetas cúbicas/cilindros estándar.

Con base en los resultados de investigaciones experimentales realizadas por varios investigadores sobre la resistencia a la compresión de probetas cilíndricas y cúbicas de varios tamaños, se pueden sacar las siguientes conclusiones:

- El efecto del tamaño no es constante para ninguna geometría de muestra. El efecto del tamaño es más pronunciado en las probetas cúbicas que en las cilíndricas. Se encontró que la desviación estándar de la resistencia disminuía a medida que aumentaba el diámetro. Se observó que la resistencia en las probetas cilíndricas se acercaba a un valor constante más allá de 600 mm (27.5 pulgadas);
- La relación de resistencia es más sensible a *h/d* para *h/d* < 1.5 que para *h/d* > 1.5. La influencia de la esbeltez de la muestra disminuye significativamente al aumentar la resistencia a la compresión del concreto. Para CUAD, la relación de resistencia a la compresión entre el cilindro y el cubo es cercana a 1.0[10]. El tamaño máximo del agregado no influye en la relación de resistencia a la compresión para CUAD[10]. Cuando se mantiene constante la esbeltez, la resistencia a la compresión de CRN, CAR y CUAD solo cambia marginalmente para diferentes tamaños de probetas;
- No existe una relación definida entre las resistencias a la compresión de varias formas de probetas; sólo existen conversiones empíricas. Al utilizar dichos factores de conversión, se deben considerar varios parámetros (incluido el nivel de resistencia, el tipo de concreto, el tamaño/gradación del agregado, el recubrimiento, el material del molde, las condiciones de curado, los métodos de consolidación y la edad de la muestra) que afectan estas conversiones para elegir el factor más adecuado[11];
- Los cilindros con diámetros de 100 mm y 76 mm y los cubos con lados de 100 mm son especímenes de prueba aceptables e intercambiables para la determinación de la resistencia a la compresión de CUADRF[10]; y
- El efecto del tamaño en CAR aún no se comprende completamente. Existe un debate sobre si el efecto del tamaño es más pronunciado en concreto de menor o mayor resistencia[11].

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La traducción de este artículo correspondió al Capítulo de República Dominicana

Título: Efecto del tamaño y forma de la probeta en la resistencia a la compresión del concreto

Traductor:
Dr. Fray F. Pozo-Lora

Revisor Técnico:
Ing. Piero Caputo