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Enhancing concrete testing : Impact of modified specimen geometry on compressive and tensile strength

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Abstract. Frequently used in mechanical testing of concrete, cubic and cylindrical shapes are the subject of a number of studies questioning their influence on the material's strength. The aim of this study was to introduce a modified geometry to reduce the volume of test specimens and guarantee improved performance in strength tests, by investigating the effect of shape. Experimental results showed that the compressive strength of the modified shape was superior to that of standard shapes. However, due to its configuration, tensile strength was slightly improved. A regression analysis was carried out based on Bazant's formula for the effect of size. The results obtained indicate that this formula can be used to explain the proposed shape effect. In this respect, an empirical formula was proposed relating the compressive strength of the proposed specimens to the strength of standard specimens. A verification of the specimen damage model was also carried out in accordance with standards. Finally, a comparative analysis of the proposed geometry with existing literature was carried out.

Keywords: compressive strength; concrete; shape effect; size effect; tensile strength

1. Introduction

In the construction industry, concrete is one of the most widely used materials. Composed of 4 main elements : aggregates, sand, cement and water, the concrete mix must satisfy specific requirements regarding its mechanical properties before it can be poured. To verify these mechanical properties, tests are carried out in the laboratory on standardized specimens. Among the most commonly used tests are the compression test, the splitting tensile test and the flexural strength test (Sadeq *et al*. 2022). These tests are conducted according to well-defined standards and requirements.

In accordance with several standards (NM 10.1.067 2008a and EN 12390-1 2001a), there are 3 possible shapes : cubic, cylindrical or prismatic. The standard specifies the dimensions and tolerances possible for each shape. According to scientific literature, certain mechanical properties are affected by specimen shape and size, namely compressive strength and splitting tensile strength. Previous works have used a variety of specimen shapes and sizes to study their influence on the strength of concrete, and to quantify this influence in equations. Bazant (1984), one of the first authors to explore this phenomenon, asserts that the effect of size results from an interaction between the notion of strength or yield strength and fracture mechanics. On the other hand, he indicates that the size effect also implies an energy effect, i.e., a discrepancy between the size dependence of the energy release rate and the energy consumption rate per fracture (Bazant 2000).

According to previous studies, the influence of size on the mechanical properties of concrete depends on several factors, such as the choice of aggregate dimensions, the type of cement used, the formulation of the concrete chosen for the project and the additives that can be included in the concrete mix. Smaller specimens tend to have higher mechanical properties than larger ones. Mansur and Islam (2002) conducted an experimental study on the effect of size of cubic and cylindrical specimens of different sizes. In this study, 11 different concrete mixes were used. The study carried out allowed us to develop relationships between the compression of a standardized cubic specimen and other specimens of different non-standard sizes. The results show that the compressive strengths of cubic specimens are higher than those of cylinders, and smaller specimens have higher compressive strengths than larger ones. Using the 3 shapes : cubic, cylindrical and prismatic, Yi *et al*. (2006) investigated the effect of size and geometric shape on the compressive strength of concrete. The findings show that, for the same type of geometry, compressive strength decreases with increasing size. Comparing the 3 shapes studied, cubic specimens have the highest compressive strengths, while cylindrical specimens have the lowest. The variation in compressive strength of concrete can also be influenced by the water-cement ratio, Yazıcı and Sezer (2007) in his work examined the variation in compressive strength for two different cylinder sizes and 8 different mixes with different water-cement ratios. As a result, it was concluded that the smaller the specimen size the greater the compressive strength, and also by decreasing the water-

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cement ratio the compressive strength increases. A similar conclusion was drawn from the research of Del Viso *et al*. (2008), in which he compared two geometric shapes : cubic and cylindrical, varying the specimen dimensions. The outcome of this study indicates that the shape and size of the specimen influence its compressive strength.

The effect of size has also been exploited on other types of concrete, namely Dehestani *et al*. (2014) used the self-consolidating concrete with 3 different mixes, and varying the height-diameter ratio. Generally speaking, as this ratio increases, compressive strength decreases. Meanwhile, Fládr and Bílý (2018) used the high-strength fiber reinforced concrete with 6 different mixes and 4 different sizes. Based on the results obtained, a linear regression was proposed. This same concrete structure was reviewed by Khalilpour and Dehestani (2022) and in addition a proposal to change the cement mix with silica fume was examined, it was found that as the amount of fiber added increases the effect of size becomes less significant, this also applies to the use of silica fume with a large quantity. In a further study carried out by Dehghanpour and Yilmaz (2020), using the electrically conductive concrete, the effect of size on resistivity and compressive strength was investigated. Standard specimen geometries : Cube, cylinder and prismatic were used in several different sizes. The results showed that as specimen size increases, resistivity increases, but compressive strength decreases. By substituting the rubber aggregate for the fine aggregate, A. Valizadeh *et al*. (2020) examined the effect of the size of the self-compacting rubberised concrete. The results of this study indicate that for the three different mixes used, compressive strength increases with decreasing specimen size, while using higher percentages of rubber aggregates reduces concrete strength. Following the same vision of modifying concrete structure, Zhu *et al*. (2022) integrated the Polypropylene fiber into the concrete mix to explore the impact of size, using three different sizes of the cubic shape. As regards the main results, it was shown that the mechanical performance of this type of concrete, in terms of compressive and tensile strength, becomes weaker with increasing specimen size. The influence of size was examined in dynamic mode by Li *et al*. (2018), who elaborated on the comparison with static mode. The results of the static tests obtained are in agreement with the results established in the literature : small specimens tend to have a higher compressive strength than larger specimens. However, the effect of size is insignificant in the dynamic test results. In investigating the effect of aggregate size, S. Rangari *et al*. (2018) also highlighted the parameter of aggregate size, finding that not only does compressive strength decrease with increasing specimen size, but it also increases with decreasing aggregate size. This result was also supported by the tests conducted by Vu *et al*. (2022), in which cylindrical specimens of different diameters were used. Two distinct concrete mixes were employed, one featuring a maximum aggregate diameter of 20 mm and the other with a maximum aggregate diameter of 40 mm. The findings of this study indicate that compressive strength decreases either with increasing specimen size or with increasing aggregate size. Using the pervious concrete, Chockalingam *et al*. (2023) demonstrated that the mechanical characteristics of this type of concrete mixture, notably its compressive strength, increase with decreasing specimen size or aggregate size.

The effect of size also has an influence on tensile strength. As demonstrated by Jin *et al*. (2019) through numerical simulation, using double-edge notched specimens, the dynamic tensile strength increases with decreasing specimen size. A direct tensile test is often complicated to perform on standardized concrete specimens (Sadeq et al. 2022). Accordingly, in his research, Resan *et al*. (2020) has proposed a new specimen geometry capable of converting a compressive force into a tensile force. The results of this research enable higher tensile strengths to be obtained compared with the traditional methods used for tensile testing, more specifically the splitting tensile test. Another approach employed for conducting tensile tests on concrete specimens involves the utilization of the Split-Hopkinson Pressure Bar test, commonly carried out with cylindrical specimens. Zhong *et al*. (2021) exploited this test using several sizes of cylindrical specimens to study the effect of size on tensile strength, as a result it was proved that by increasing the size of specimens we get higher performance of the splitting tensile strength. The effect of size on tensile strength was also examined on other types of concrete mix. Taking the example of the ultra-high-performance fibre-reinforced concrete, which was used by Maryamh *et al*. (2022) to conduct a tensile test using five different sizes. As previously established, smaller specimens tend to have higher tensile strength than larger ones. Tensile strength is influenced not only by size, but also by the geometric shape of the specimens. Wu *et al*. (2022) conducted a numerical research to evaluate the performance of coral aggregate concrete as regards its tensile strength. The output of this study shows that the splitting tensile strength of the cylindrical specimens is lower than that of the cubic shape.

Lastly, variations in specimen size can also influence the flexural strength of concrete, Sengun *et al*. (2023) demonstrated that the smaller the specimen size, the greater the flexural strength.

In this paper, the concept of a modified specimen geometry was proposed, based on the principle of reducing specimen size while guaranteeing better performance than standard specimens. Experimental investigations were carried out to compare and analyze the compressive and tensile strength results of standard and proposed specimen shapes.

2. Experimental procedure

2.1 Description of the geometrical shape

As mentioned in the section above, concrete characterization tests are carried out on three main shapes : cubic, cylindrical, and prismatic. As part of the development of these shapes, wooden hexagonal prism molds were designed to produce the test specimens. The idea for this design came from the honeycomb cell form,

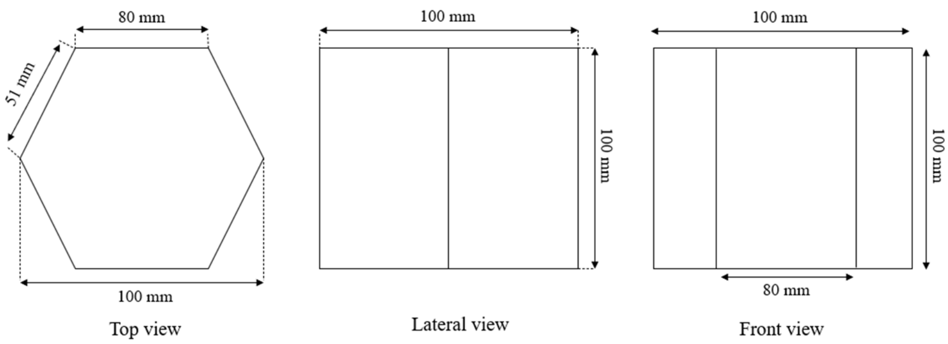


Fig. 1 The proposed hexagonal shap

Table 1 Final composition of 1 m^3 of concrete used

	Element	Crushed sand	Gravel type GI	Gravel type GII	Cement	Water	Maximum diameter (mm)	Water-cement ratio
Mix 1	Quantity in Kg/m^3	912	509	411	330	214	25	0,65
Mix 2		646	462	360	330	205	20	0,62

which is known for its high strength and reliability and is employed in a number of fields, including aeronautics and the automotive industry. Hexagonal specimens also offer a reduction in volume, leading to a reduction in the raw materials used to manufacture them, which in turn decreases laboratory waste.

While cubic and cylindrical specimens are widely used due to their ease of production and quality control, exploring alternative geometries remains relevant for applications where non-standard shapes may be required. Hexagonal prisms could be advantageous in modular construction and precast elements while also contributing to material efficiency and sustainability. Understanding the influence of specimen shape on mechanical properties is particularly important as construction technologies continue to evolve.

Fig. 1 illustrates the design of the hexagonal specimens used. The dimensions selected adhere to the standard specifications of a 100 mm cube.

2.2 Description of concrete composition

In the context of this study, two different mixes were used. In order to prepare the specimens, ordinary portland cement class CPJ 55 was used. Compressive strength at 28 days was set at 25 MPa with a safety factor of 15%. The purity of the crushed sand used is 70%. Finally, the selected concrete subsidence is 9 cm. The first mix features a water-cement ratio of 65% alongside a maximum aggregate diameter of 25 mm, while the second mix presents a water-cement ratio of 62% with a maximum aggregate diameter of 20 mm.

Table 1 presents the final composition adopted for 1 m^3 of concrete of both mixes used in this study.

A total of 18 specimens were produced from each mix, including : 6 cylindrical specimens sized Ø 160 × 320 mm, 6 cubic specimens sized 100 mm and 6 hexagonal specimens. Fig. 2 shows the hexagonal and cubic specimens

Fig. 2 The hexagonal and cubic specimens

obtained.

During the preparation of the specimens, it was necessary to ensure that all air bubbles were removed. For this purpose, a vibration was applied to the cylindrical specimens using an electric vibrator, while for the other shapes, the specimens were manually vibrated until all air bubbles disappeared completely off the surface. The planarity of the top surface of all the specimens was checked.

Following the fabrication of the specimens, they were carefully positioned in a water tank within a controlled environment. The designated room maintained a relative humidity exceeding 95% and a temperature of 20°C ± 2. This setup was planned to enable the crystallization of the cement, in perfect accordance with the requirements stated in the standards (PNM 10.1.068, 2008 and EN 12390-2, 2001). This controlled environment was sustained for a duration of 28 days.

2.3 Experimental procedure

In the present research, compression and splitting tensile tests were carried out on the 18 specimens : for each test, three specimens of each shape were examined. Compression tests were carried out using an automatic

Fig. 3 Experimental device for compression test on the left and splitting tensile test on the right

compression machine at a speed of 0.5 MPa/s in accordance with the standards (NM 10.1.051 2008 and EN 12390-3 2003), while for split tensile tests, the same machine was used, with the addition of a specific mold to obtain the tensile force as illustrated by Fig. 3. The speed of the splitting tensile test was set at 0.05 MPa/s in accordance with the standards (NM 10.1.052 2008 and EN 12390-6 2001).

3. Experimental results and discussion

Table 2 summarizes the results of the compression and tensile tests carried out in this study. The table also indicates the nomination chosen, as well as the geometric shape for each specimen.

3.1 Compression and tensile test results

According to the obtained results, the hexagonal specimens demonstrated a higher compressive performance than the standard specimens (cubic and cylindrical) in both mixtures. As established in previous studies, cubic specimens generally offer higher compressive strengths than cylindrical ones due to their reduced lateral surface area, which leads to lower friction losses and more uniform stress distribution during testing (Mansur and Islam 2002, Li *et al*. 2018, Wu *et al*. 2022). In this study, mixture no. 1 showed that the hexagonal specimens achieved an average compressive strength of 33.40 MPa, compared to 30.53 MPa and 25.06 MPa for cubic and cylindrical specimens, respectively. Similarly, in mixture no. 2, the hexagonal specimens reached 34.42 MPa, while the cubic and cylindrical specimens exhibited average strengths of 31.72 MPa and 26.12 MPa, respectively.

The superior performance of the hexagonal specimens can be attributed to their geometrical configuration, which offers improved load distribution and reduces the presence of stress concentration points. The hexagonal shape may promote more uniform axial stress paths and limit the initiation of premature failure planes, especially when compared to cylindrical specimens that are more prone to end effects and stress irregularities. Furthermore, the

Table 2 Results of compression and tensile splitting tests

Mix	Specimen reference	Shape	Compressive strength (MPa)	Tensile strength (MPa)
Mix 1	M1Cy1	Cylindrical	24,57	3,15
	M1Cy2		25,15	3,36
	M1Cy3		25,46	3,26
	Average strength		**25,06**	**3,26**
	M1Cu1	Cubic	30,16	3,41
	M1Cu2		31,16	3,67
	M1Cu3		30,26	3,54
	Average strength		**30,53**	**3,54**
	M1Hx1	Hexagonal	33,75	3,55
	M1Hx2		32,95	3,75
	M1Hx3		33,50	3,64
	Average strength		**33,40**	**3,65**
Mix 2	M2Cy1	Cylindrical	25,50	3,75
	M2Cy2		26,35	4,16
	M2Cy3		26,50	3,97
	Average strength		**26,12**	**3,96**
	M2Cu1	Cubic	30,58	4,25
	M2Cu2		31,22	4,20
	M2Cu3		33,37	3,84
	Average strength		**31,72**	**4,10**
	M2Hx1	Hexagonal	33,96	4,45
	M2Hx2		34,58	4,26
	M2Hx3		34,73	3,95
	Average strength		**34,42**	**4,22**

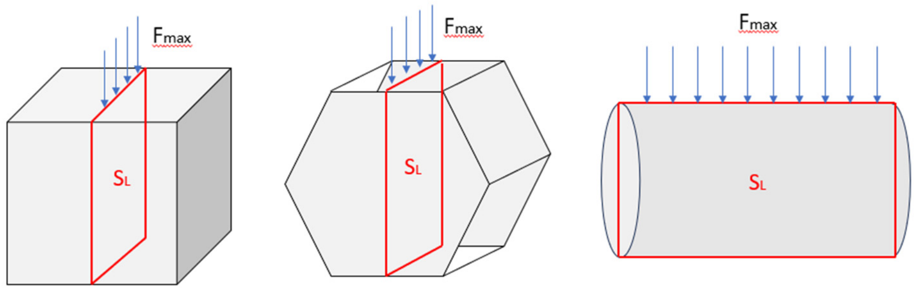


Fig. 4 Compressive load-bearing surface (S_L) of each shape

reduced specimen volume, inherent in the hexagonal design, may contribute to the increase in apparent compressive strength, as smaller specimens are often less affected by internal flaws and more likely to exhibit ideal material behavior. Overall, decreasing the specimen volume resulted in an average strength increase of approximately 3 MPa and 8 MPa when compared to cubic and cylindrical specimens, respectively.

The results of the splitting tensile test confirm that hexagonal and cubic specimens have higher strengths than cylindrical specimens in both mixtures. However, confronting the results of the hexagonal and cubic specimens, the difference between the strengths is determined by an average of 0.1 MPa. This is due to the equality of the surface subjected to compressive loads between the two shapes, as shown in Fig. 4.

By applying the formula for calculating tensile strength, the following equation is obtained

$$T_S = \frac{F_{max}}{S_L} \tag{1}$$

Where

T_s : Splitting tensile strength (MPa)

F_{max} : Maximum force applied until failure of the specimen (N)

S_L : Compressive load-bearing surface (mm²)

3.2 Conversion factors

The conversion factor is defined by the proportion between the mechanical characteristic of a standard specimen and the average of the mechanical characteristics of the non-standard specimen, i.e., the hexagonal shape in this study. The interest of this factor consists in asserting the significance of the effect of size or shape in this case. The larger the factor, the greater the significance of the effect of shape, and conversely, if the value of the conversion factor is small, the significance of the effect of shape in this case is negligible (Zhu *et al*. 2022). In order to confirm the effect of shape on the mechanical properties of the specimens, conversion factors were calculated according to the following formulas

$$F = \frac{F_c}{F_{moy}} \tag{2}$$

Where :

F : compression conversion factor

F_c : Compressive strength of cubic or cylindrical specimens (MPa)

F_{moy} : average compressive strength of hexagonal specimens (MPa)

And

$$T = \frac{T_c}{T_{moy}} \tag{3}$$

Where :

T : tensile-splitting conversion factor

T_c : Tensile splitting strength of cubic or cylindrical specimens (MPa)

T_{moy} : average tensile splitting strength of hexagonal specimens (MPa)

Table 3 The conversion factors

Specimens	F_c (MPa)	F_{moy} (MPa)	F	T_c (MPa)	T_{moy}	T
M1CY1	24,57	33,4	0,74	3,15	3,65	0,86
M1CY2	25,15		0,75	3,36		0,92
M1CY3	25,46		0,76	3,26		0,89
M1Cu1	30,16		0,9	3,41		0,93
M1Cu2	31,16		0,93	3,67		1,01
M1Cu3	30,26		0,91	3,54		0,97
M2Cy1	25,50	34,42	0,74	3,75	4,22	0,89
M2Cy2	26,35		0,77	4,16		0,99
M2Cy3	26,50		0,77	3,97		0,94
M2Cu1	30,58		0,89	4,25		1,01
M2Cu2	31,22		0,91	4,20		1,00
M2Cu3	33,37		0,97	3,84		0,91

Table 3 summarizes the results of calculating conversion factors between cylindrical and hexagonal shapes, as well as between cubic and hexagonal shapes.

As shown in Table 3, the conversion factors for cubes in both compression and tensile tests are greater than those for cylinders. In this case, it can be concluded that cubes exhibit a more pronounced size effect than cylinders do when comparing hexagonal shapes to one another.

On average, the conversion factor for compressive strength from cylindrical to hexagonal shapes is approximately 0.75, implying that the compressive strength of cylinders is 75% that of hexagons. Similarly, the average conversion factor for tensile strength from cylindrical to hexagonal shape is 0.90, indicating that the tensile strength of cylindrical specimens is 90% of that exhibited by hexagonal specimens. This reduction in volume leads to a notable improvement, with a 25% increase in compressive strength and a 10% improvement in tensile strength.

Likewise, the average compression conversion factor from cubic to hexagonal shape is 0.91, signifying that the compressive strength of the cubic configuration is 91% of that found in the hexagonal shape. Similarly, the average tensile conversion factor from cubic to hexagonal shape is 0.97, indicating that the tensile strength of cubes is 97% of the tensile strength observed in hexagonal specimens. As a result, a 10% reduction in volume translates to an improvement of 9% in compressive strength and a 3% enhancement in tensile strength.

3.3 Verification of the size effect law

The preceding research has suggested a variety of models representing the influence of size on the properties of concrete. Among the best-known models is the Bažant (1984) model represented by the following formula

$$\sigma_n = \frac{CF_t}{\sqrt{1 + \frac{d}{d_0}}} \tag{4}$$

Where, σ_n (MPa) is the nominal stress, F_t (MPa) is the material's tensile strength, C is the non-dimensionalized constant, d (mm) is the characteristic dimension of the structure, d_0 (mm) is a constant associated with the structure's geometry.

On the other hand Kim and Yi (2002) have also proposed a model involving the height and diameter of the specimens as main parameters, the formula of the model is presented as follows

$$\frac{F}{F_c} = \frac{0,4}{\sqrt{1+\frac{h-d}{50}}} + 0,8 \tag{5}$$

Where F (MPa) is the compressive strength of a cylinder having height h (mm) and diameter d (mm) and Fc (MPa) is the compressive strength of standard cylinder.

An interesting third model is suggested by Neville (1966), who carried out tests on different specimen shapes with different h/d ratios. The model takes into account specimen height, lateral diameter and volume. The model is presented as follows

$$\frac{f_c}{f_{cu}} = 0,56 + 0,697\,\frac{d}{\frac{V}{150\,h} + h} \tag{6}$$

Where f_c (MPa) is the compressive strength measured using a cylindrical, cubic, or prismatic specimen, f_{cu} (MPa) is the strength of a standard cube, d (m) is the maximum lateral dimension, V (m^3) the volume and h (m) the height.

The results of compression tests of the proposed shape of the two mixtures were used to verify Bazant's size effect law mentioned in Eq. (4). In this context, the relationships employed in this study are given as follows

$$\frac{F_{Hx}}{F_{Cu}} = \frac{a}{\sqrt{1+\frac{D}{D_0}}} + b \tag{7}$$

And

$$\frac{F_{Hx}}{F_{Cy}} = \frac{a}{\sqrt{1+\frac{D}{D_1}}} + b \tag{8}$$

Where F_{Hx}, F_{Cu} and F_{Cy} represent the compressive strengths of the hexagonal, cubic and cylindrical shapes respectively. D, D_0 and D_1 represent the lengths of the long diagonal of each shape as shown in Fig. 5. Factors a and b were calculated using linear regression from the plot of the F_{Hx}/F_{Cu} curve as a function of $1/\sqrt{(1+D/D_0)}$ and the F_{Hx}/F_{Cy} curve as a function of $1/\sqrt{(1+D/D_1)}$. Fig. 6 shows the two curves and the linear regression equations.

Given the regression results in Fig. 6, the coefficients of determination R^2 found are 0.877 and 0.8402 for the hexagonal versus cubic curve and the hexagonal versus cylindrical curve respectively. The R^2 values prove that the experimental results obtained are reasonably well fitted to the proposed model, which means that the Bazant's law can be applied in this case to explain the variation in the effect of geometric shape proposed in this work.

By the same logic, the results of the tensile test were used to verify Bazant's size law by adopting the following equations

$$\frac{T_{Hx}}{T_{Cu}} = \frac{a}{\sqrt{1+\frac{D}{D_0}}} + b \tag{9}$$

And

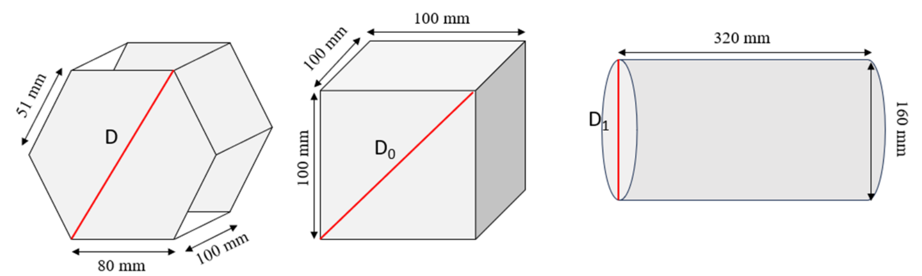
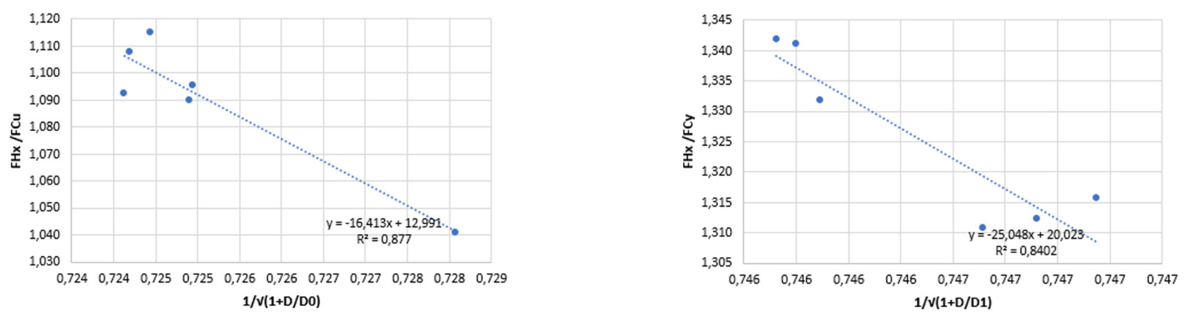
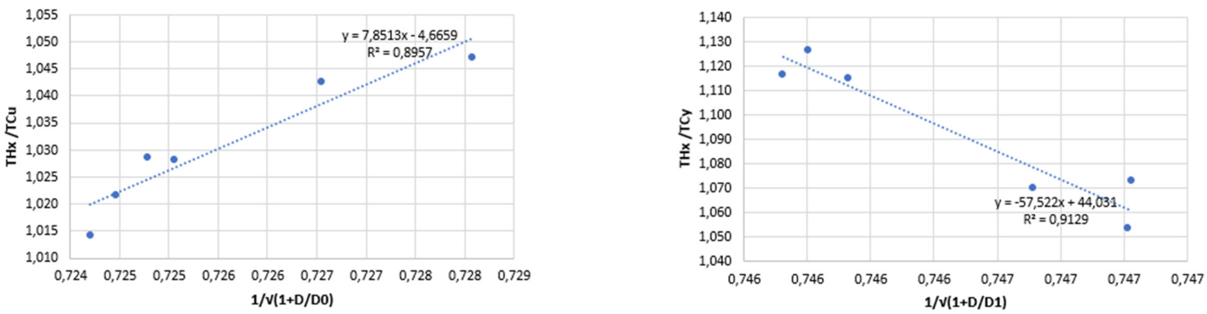


Fig. 5 The long diagonal of each shape



(a) The F_{Hx}/F_{Cu} curve as a function of $1/\sqrt{(1+D/D_0)}$ (b) The F_{Hx}/F_{Cy} curve as a function of $1/\sqrt{(1+D/D_1)}$

Fig. 6 Regression curves based on Bazant's size effect law of compression results



(a) The T_{Hx}/T_{Cu} curve as a function of $1/\sqrt{(1+D/D_0)}$ (b) The T_{Hx}/T_{Cy} curve as a function of $1/\sqrt{(1+D/D_1)}$

Fig. 7 Regression curves based on Bazant's size effect law of tensile results

$$\frac{T_{Hx}}{T_{Cy}} = \frac{a}{\sqrt{1+\frac{D}{D_1}}} + b \tag{10}$$

Where T_{Hx}, T_{Cu} and T_{Cy} represent the splitting tensile strengths of the hexagonal, cubic and cylindrical shapes respectively. The factors a and b were calculated using linear regression from the plot of the T_{Hx}/T_{Cu} curve as a function of $1/\sqrt{(1+D/D_0)}$ and the T_{Hx}/T_{Cy} curve as a function of $1/\sqrt{(1+D/D_1)}$. Both curves are shown in Fig. 7, along with the equations derived from the linear regression.

According to Fig. 7, the values of the coefficients of determination R^2 found are 0.8957 for the hexagonal versus cubic shape curve and 0.9129 for the hexagonal versus cylindrical shape curve. The R^2 values indicate that the adjustment of the experimental results resulting from the proposed model is very good and therefore Bazant's law can be exploited to formulate a law outlining the influence of geometry on resistance.

3.4 Failure model

According to standards (NM 10.1.051 2008 and EN 12390-3 2003), specimen fracture is considered to be correct if it follows certain specific shapes. The lateral surface of the specimen undergoes similar cracking, without significant damage to the surfaces in contact with the compression machine platens. Fig. 8 shows the correct fractures of cubic and cylindrical shapes according to this standard.

In Fig. 9, the fracture patterns obtained for the three shapes are illustrated. Subsequently, in Fig. 9 : (a) depicts the fracture pattern of the cubic shape, (b) showcases the fracture pattern of the cylindrical shape, and (c) presents the fracture pattern of the hexagonal shape on the left, juxtaposed with the fracture pattern of the cubic shape on the right. Notably, the failures observed for all three shapes, identified as conical failures, adhere to the specified standards for proper failure shapes.

During the crushing of hexagonal specimens, it was found that cracking starts on the small-area side faces, followed by the appearance of cracks on the other two remaining faces. The cracking therefore propagates and becomes larger. The damage to the specimens becomes more consistent at the core as the applied force increases. Similarly for the other two shapes, cubic and cylindrical, crack initiation is localized at the lateral surfaces of each shape (all 4 sides in the case of the cube), with subsequent damage concentrated in the middle of the specimen, leaving a conical shape at the end of the test.

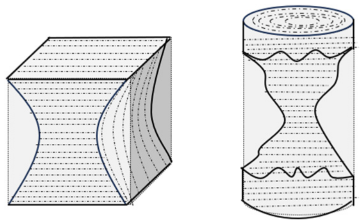


Fig. 8 Proper fractures of cubic and cylindrical shapes according to standards (NM 10.1.051 2008 and EN 12390-3 2003)

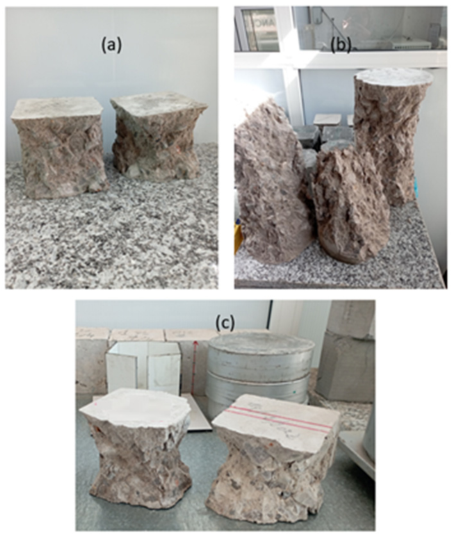


Fig. 9 Failure profile obtained for the three shapes

3.5 Compatibility of the proposed geometric shape with the scientific literature

In this last section, a comparison of the performance of the proposed geometric shape with the performance of the various other shapes from previous scientific studies was investigated. Table 4 shows the different shapes used in each study, the water-cement ratio (W/C) used and the

Table 4 Compression test results for each study

	Designation	Shape	Dimensions	W/C (%)	Compressive strength (MPa)		
This study	M1Hx	Hexagonal prism	Dimensions are shown in Fig. 1	65	33,75	32,95	33,5
	M2Hx			62	33,96	34,58	34,73
	M1Cu	Cubic	100 × 100 × 100	65	30,162	31,162	30,262
	M2Cu			62	30,58	31,22	33,37
	M1Cy	Cylindrical	320 × Φ160	65	24,57	25,15	25,46
	M2Cy			62	25,50	26,35	26,50
Yi *et al.* (2006)	Yi-Cu	Cubic	100 × 100 × 100	67	30,9	32	33,8
	Yi-Cy	Cylindrical	300 × Φ150		26,8	27,2	27,1
	Yi-Pr	Prism	150 × 150 × 300		27,1	26,4	26,9

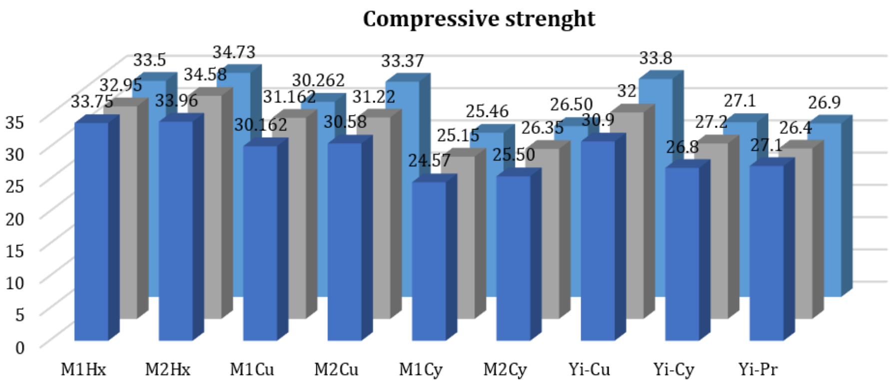


Fig. 10 Comparison of compression test results

Table 5 Comparison of tensile test results of the two studies

	This study				Resan *et al.* (2020)					
W/C (%)	65				42					
Shape	T_{M1Hx}/T_{M1Cy}	T_{M1Hx}/T_{M1Cu}	T_{M2Hx}/T_{M2Cy}	T_{M2Hx}/T_{M2Cu}	Resan's model	Resan's model	Cylindrical	Cylindrical	f_{M1}/f_{Cy1}	f_{M2}/f_{Cy2}
Designation					S.F-M1	S.F-M2	S.F-Cy M1	S.F-Cy M2		
Tensile strength (MPa)	1,13	1,04	1,19	1,05	2,27	1,92	2	1,82	1,14	1,06
	1,12	1,02	1,02	1,01	2,39	2,08	2	1,92	1,2	1,08
	1,12	1,03	0,99	1,03	2,56	2,23	2,4	2,01	1,07	1,11

results of the compression test.

Fig. 10 summarizes the comparison between the results of the two studies. In Yi *et al.* (2006), the results for the standard shapes were selected. For a W/C ratio of 67%, the results indicate that the cubic shape, being the smallest in volume, achieves a more significant compression efficiency than the cylindrical and prismatic shapes. In comparison with the hexagonal shape proposed and for a W/C ratio of 65% and 62%, it was found that on average the hexagonal shape has a higher compressive strength than the shapes studied at Yi *et al.* (2006).

As regards the tensile test, the results of this study were compared with those of the model established in the paper authored by Resan *et al.* (2020). Taking into account that the composition of the concrete mix used is different, including the W/C ratio chosen, it was more appropriate to compare the performance of the tensile strength ratios of the hexagonal shape to the tensile strengths of the cylindrical and cubic shapes in this study and the tensile strength ratios of the Resan *et al.* (2020) model to the tensile strength of standard cylinders for the two mixes used.

Table 5 presents a summary of the comparison results. In the table, T_{MiHx}, T_{MiCy} and T_{MiCu} denote the splitting tensile strengths of hexagonal, cylindrical, and cubic specimens, respectively. The labels M1 and M2 correspond to the mixture numbers. While f_M and f_{Cy} represent the tensile strengths of the proposed model and cylindrical shapes, as utilized by Resan *et al.* (2020), respectively. Additionally, Indications 1 and 2 denote the outcomes of mixtures 1 and 2, respectively.

The outcomes of the table indicate that on average the ratios T_{M1Hx}/T_{M1Cy} and f_{M1}/f_{Cy1} are identical, as are the ratios of T_{M2Hx}/T_{M2Cy} and f_{M2}/f_{Cy2}. However, the average ratios of T_{M1Hx}/T_{M1Cu} and T_{M2Hx}/T_{M2Cu} appear to be relatively smaller. Consequently, it can be assumed that the results for the hexagonal shape are compatible with the results of the model proposed by Resan *et al*. (2020).

4. Conclusions

According to the results obtained from the experimental study carried out in this paper, optimizing the specimen volume improves concrete strength performance : a 10% optimization increases compressive and tensile strength by 9% and 3%, respectively. Thus, variation in specimen shape has a significant effect on the compressive and tensile strengths of concrete. The findings of this study affirm that the compressive strengths of the cubic and cylindrical shapes comprise 90% and 75%, respectively, of the strength observed in the hexagonal shape. Likewise, the splitting tensile strengths of the cubic and cylindrical shapes constitute 97% and 89%, respectively, of the strength exhibited by the hexagonal shape.

Beyond strength improvements, the use of hexagonal specimens offers potential benefits in material efficiency and sustainability, as the reduced volume leads to lower raw material consumption and laboratory waste. These findings suggest that alternative geometries could be considered in applications requiring optimized material use, particularly in modular and prefabricated construction. Furthermore, with the growing adoption of advanced techniques such as 3D printing, understanding the mechanical behavior of non-standard specimen shapes becomes increasingly relevant for future construction innovations.

Utilizing the experimental data outlined in this paper, empirical formulas have been formulated employing Bazant's size effect law. These formulas establish correlations between the compressive and tensile strengths of hexagonal structures and their counterparts in standard shapes. On the other hand, analysis of the damage pattern of the hexagonal specimen reveals that the first cracks form on the smallest lateral surfaces. Subsequently, these cracks propagate uniformly across all surfaces until the specimen bursts, resulting in a double-conical configuration at the end of the test.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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