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SPECIMEN SIZE AND SHAPE EFFECT ON THE COMPRESSIVE STRENGTH OF CONCRETE

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Summary. *The results of the investigation of the specimen size and shape effect on concrete strength indicators are presented in this paper. Research on the strength of concrete specimens in the form of cubes (150x150x150 mm) and cylinders of different diameters (50 mm, 100 mm and 150 mm) and heights (100 mm, 200 mm and 300 mm), under compression are carried out on Matest testing machine with Servo-Plus Evolution servo-drive control unit. Three specimens of each type are tested. Control specimens are made according to such ratios of materials that concrete corresponds to the strength class C16/20. All specimens are visually inspected for the presence of any defects, such as large pores, chips, or shrinkage cracks. After that, the actual measurements of all specimens are carried out. They showed minimal deviations from the planned size, which is considered acceptable. In order to check the reliability of the results, after the research of each type of specimen, calculations are carried out to determine the actual strength and the concrete grade. The actual dimensions of the faces and the results of the certain batch research are taken. The data obtained from the concrete specimens research on the test press are analyzed. Due to the formulas and data obtained after the investigation, the actual strength class of concrete for all specimens is determined. According to the results of the research, fracture graphs of all types of control specimens are constructed. The results show that the laboratory measurements are consistent with the literature results, namely that the compressive strength decreases with the specimen size increase. In the case of the smallest, non-standardized specimens (cylinders with 100 mm height and 50 mm diameter), the deviation of compressive strength tests is higher compared to other specimens. The graph is presented for visualizing the specimen type and size effect on concrete strength.*

Key words: *compressive strength, concrete specimen, size effect, shape effect.*

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Statement of the problem. It is not easy to imagine the construction of residential or industrial buildings without the use of concrete. Nowadays, it is the principal, essential structural material for almost any construction project. To a great extent, the quality of concrete depends on its strength and durability [1, 2]. The strength of concrete characterizes its ability to resist mechanical and chemical effects and is the most important parameter determining the properties and operational qualities of building structures and elements [3].

The ability to determine precisely the concrete strength makes it possible to avoid many undesirable consequences of structures. For example, the application of concrete with insufficient strength level can result in the decrease of operational factors of the building or structure, the occurrence of cracks, premature fracture and premature failure of the building. Concrete strength determination is compulsory for builders before putting the building into operation [4].

Destructive and non-destructive [5, 6] methods of concrete strength determination are known. Destructive methods involve fracturing the specimen made of concrete mixture or concrete cut off from the structure. During this experimental method, cubes or cut concrete cylinders should be tested. The load increases continuously and uniformly until the failure of a specimen. The critical load is recorded, and further concrete strength can be calculated. The destructive method is considered to be the most accurate determination of concrete strength by crushing concrete specimens. According to the current standards [7–9] such a test is compulsory to put the building into operation.

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Based on the works of many researchers, it has become a well-known fact that the concrete specimen size and shape affect its strength [10–12]. For standardization purposes, the concrete compressive strength is measured on the standard cylinder (150 mm x 300 mm) or on the cube (150 mm x 150 mm x 150 mm) and is accepted as a unique material property. However, the concrete compressive strength is not unique; it depends on the specimen size and shape due to their fracture characteristics. The so-called size effect law (SEL) was first derived by Bazant.

After that, Kim and others proposed formula (1), the size-independent strength to SEL that calculates approximately the nominal strength of concrete elements that have similar or different crack patterns.

$$\sigma_N(d) = \frac{B f_t' 1}{\sqrt{1+ {d}/{\lambda_0 d_a}} + \alpha f_t'}, \tag{1}$$

The paper aims to evaluate the effect of types and sizes of control specimens on the concrete strength.

Methods of experimental investigation. Two specimen shapes – the cube and the cylinder (Fig. 1) were made for experimental investigations. Three cubes with 150 mm edge size and nine cylinders with three different diameters d1 = 50 mm, d2 = 100 mm, d3 = 150 mm and height h = 2d were prepeared. That is, cylinder d = 50 mm, h = 100 mm – 3 pieces; d = 100 mm, h = 200 mm – 3 pieces; d = 150 mm, h = 300 mm – 3 pieces.

A study of the concrete strength of the specimens was carried out by destructive method in laboratory conditions on Matest test machine under compression on Servo-Plus Evolution control unit (Fig. 1 b).

a b

Figure 1. Cubic specimens for testing – a and photo of Matest press – b

During the experiment, cubic and cylindrical concrete specimens, a total 13 amounts of two batches were studied:

- the first batch consisted of 3 cubic specimens and 7 cylindrical with different sizes, at the age of 28 days.
- the second batch consisted of 3 specimens having the shape of the smallest cylinders, at the age of 14 days.

Table 1

Actual dimensions of cubic specimens

Specimen name	Face size, mm				Area, cm^2
	a_1	a_2	a_3	a_4	S
$Cube_1$	148	150	152	148	225
$Cube_2$	149	152	150	150	225
$Cube_3$	150	149	150	150	225

The control specimens are made according to such material ratios that concrete corresponds to C16/20 strength class. All specimens are visually inspected for the presence of any defects, such as large pores, chips, and shrinkage cracks. After that, the actual measurements of all specimens are conducted. These measurements show that there are minimal deviations from the planned size. They are considered to be acceptable. The results of the measurements are shown in Tables 1 and 2.

Table 2

Actual dimensions of cylindrical specimens

Specimen name	Size, mm		Area, cm^2
	d	h	S
$Cylinder_{big}$	150	298	176.6
	150	300	
	150	299	
$Cylinder_{medium}$	100	199	78.5
	100	198	
	100	200	
$Cylinder_{small}$	50	100	19.6
	50	98	
	50	100	
	50	99	

Investigation results. According to the objective of the investigation, at first, the cubic specimens with 150x150x150 mm size and 28 days old were examined. Upon completion of the investigations, the results were analyzed. Test results of cubic specimens, which were recorded on the test press control panel, are shown in Table 3.

In order to verify the reliability of the results, calculations for the actual strength and concrete class determination were carried out after the tests of each type of specimen. For this purpose, the actual face dimensions and the results of a certain batch investigation were taken. They are presented in Tables 1 and 3.

Table 3

Generalized test data of cubic specimens at the age of 28 days

Specimen name	Maximum load F, kN	Maximum stress, MPa	Average stress, MPa
Cube	763.0	33.91	31.75
	705.9	31.37	
	674.8	29.99	

After analyzing the results, statistical data processing was carried out, and the value of concrete compressive strength was calculated:

$$fc_1 = (F \times a)/A = (763{,}0 \times 1{,}00)/225 = 33{,}91 \text{ MPa}, \quad (2)$$

where a is scaling factor for bringing the concrete strength to the concrete strength in basic size and shape specimens according to the standard [18].

The values of concrete compressive strength for the other two specimens of the batch are $fc_2 = 31{,}37$ MPa, $fc_3 = 29{,}99$ MPa.

Further, we find the average value of concrete compressive strength according to the formula:

$$fcm = \frac{fc_1 + fc_2 + fc_3}{n} = \frac{33{,}91 + 31{,}37 + 29{,}99}{3} = 31{,}75 \text{ MPa}, \quad (3)$$

where n is the number of specimens in the batch.

Next, we determine the range of unit values of concrete strength in the controlled batch Wm, which is defined as the difference between $fmax$ and $fmin$ according to formula (4):

$$Wm = fmax - fmin = 33{,}91 - 29{,}99 = 3{,}92 \quad (4)$$

After that, the mean square deviation of concrete strength in the batch is calculated:

$$s_m = \frac{Wm}{a} = \frac{3{,}92}{1{,}69} = 2{,}31, \quad (5)$$

where a is the coefficient depending on the number of unit values and is accepted according to the standard [7].

Next, the variation coefficient is determined:

$$V = \frac{S_m}{fcm} = \frac{2{,}31}{31{,}75} = 0{,}072 \quad (6)$$

Characteristic strength value and class for concrete specimens is as follows:

$$f_{ck,cube} = fcm(1 - 1{,}64 \times V) = 31{,}75\,(1 - 1{,}64 \times 0{,}072) = 28 \text{ MPa} \quad (7)$$

According to the obtained data on the concrete strength classes, for C16/20 class, the generally accepted value is 20 MPa, which differs from the calculated value of the guaranteed strength. This is due to the error in the concrete mixture manufacturing, but this deviation does not affect the research objective since all the specimens are made of the same concrete mixture. Following the standard norms [7], the actual calculated concrete strength class corresponds to C20/25 concrete class characteristics.

Based on the data obtained after the concrete specimens investigation and saved via RS232 on PC, the graph of the relationship between maximum load and specimen fracture time was constructed (Fig. 2). The speed and load start parameters were the same for all specimens.

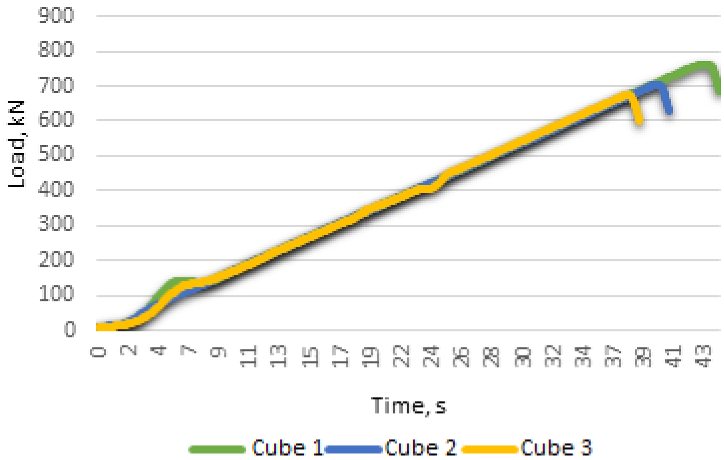

Figure 2. The graph of the dependence of the fracture time on the load for cubic specimens with 150 mm faces

After the cylindrical specimens testing, experimental data obtained from the test press control panel are analyzed and presented in Table 4.

Table 4

Test results of cylindrical specimens at the age of 28 and 14 days

Specimen name	Maximum load *F*, kN	Maximum stress, MPa	Average stress, MPa
age 28 days			
$Cylinder_{big}$	493.7	27.93	26.62
	464.5	26.28	
	453.4	25.66	
$Cylinder_{medium}$	287.0	36.54	35.47
	275.8	35.11	
	267.6	34.74	
$Cylinder_{small}$	39.1	19.92	19.92
age 14 days			
$Cylinder_{small}$	29.6	15.08	11.87
	22.3	11.37	
	18.0	9.17	

Similarly, statistical processing of the data of concrete specimens of large cylinders with 100 mm diameter (height 200) and 150 mm (height 300 mm) and age of 28 days was carried out.

According to the data on concrete class strength, for C16/20 class, the generally accepted strength is 20 MPa, which, as in the case of cubes, differs from the calculated value of the guaranteed strength. This result could be due to minor errors in the concrete components manufacturing. Such deviation does not affect the assigned tasks of the work.

Therefore, the actual calculated concrete strength class corresponds to C20/25 class characteristics.

According to the data presented in Table 4, the graph of the dependence between maximum load and time of specimen fracture is plotted (Fig. 3). The speed and load start parameters are the same for all specimens.

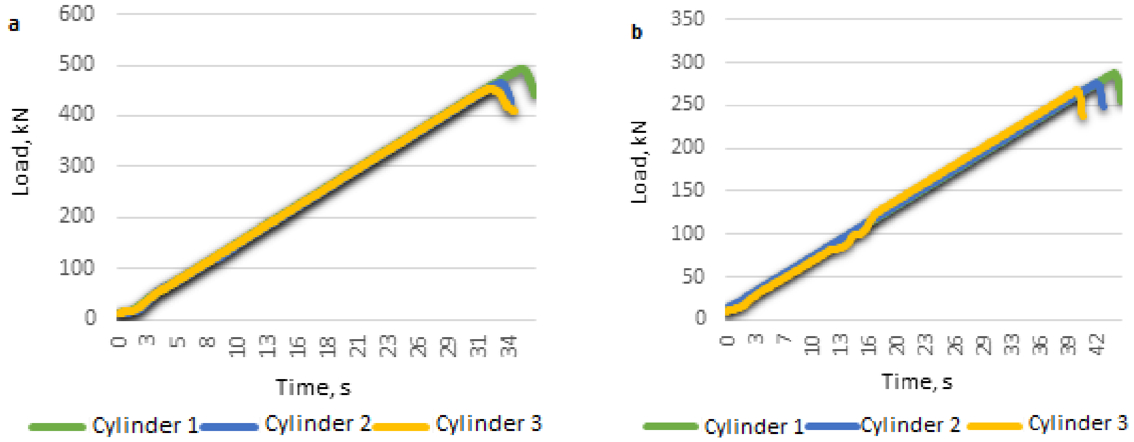

Figure 3. Graph of the dependence of fracture time on the load for large cylindrical specimens with 150 mm – a and 100 mm – b in diameters

Next, the small cylinder with 50 mm diameter and 100 mm height at the age of 28 days was tested. Since the other two specimens of this batch were found to be defective, it was impossible to carry out a complete calculation of the characteristic value of compressive strength of the concrete batch.

Therefore, according to the data on concrete strength classes, where the strength for C16/20 class is 20 MPa, it can be assumed that the specified cylindrical specimen does not correspond to the design concrete class. Its actual concrete class is C12/15.

According to the data obtained after the investigation of the specified concrete specimen and saved via RS232 on PC, the graph of the dependence between maximum load and specimen fracture time was constructed (Fig. 4 a). Parameters of the loading rate and the beginning of loading were set the same as for the previous specimens.

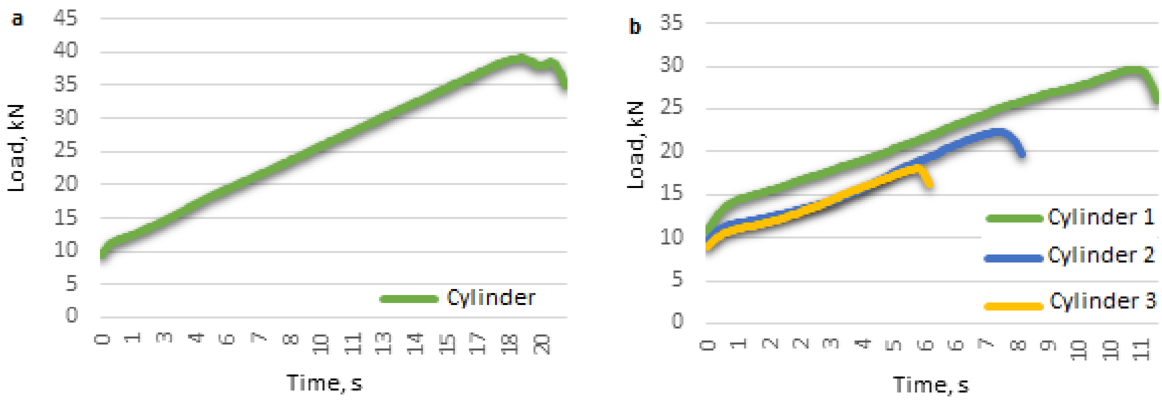

Figure 4. Graph of the dependence of the fracture time on the load for large cylindrical specimens with 50 mm diameter at the age of 28 days – a and 14 days – b

The last to be tested was the batch of three small cylinder specimens with 50 mm diameter and 100 mm height at the age of 14 days.

According to the data presented in Table. 4, the graph of the dependence between maximum load and specimen fracture time was constructed (Fig. 4 b). The parameters of the speed and the beginning of loading were the same for all specimens.

Specimens aged 28 and 14 days were tested. Concrete specimens were of two types, cylindrical and cubic shapes, in total 13 pieces. All data were analyzed and presented in Tables 3 and 4. The tables indicated the maximum load and stress of each specimen and the average stress in the batch. According to the results, the diagrams of specimen fracture (Fig. 2 – Fig. 4), depending on fracture time and maximum load, were constructed. To compare the obtained data, all the results were listed in Table. 5.

Table 5

Combined test results of three concrete specimens batches aged 28 days, after tests on Matest hydraulic press

Specimen type	Concrete design class	Actual concrete class	Average concrete strength, MPa
Cube	C16/20	C20/25	31.75
Cylinder_{big}	C16/20	C20/25	31.96
Cylinder_{medium}	C16/20	C30/35	40.9
Cylinder_{small}	C16/20	C12/15	18.95

The average concrete strength for the batch of small cylinders aged 14 days is 11.28 MPa. From the calculation results, it is obvious that the guaranteed strength class of the batch of small cylindrical specimens aged 14 days is the lowest. This is due, particularly, to the fact that concrete has not gained the required strength in 14 days. It also means that it is not reasonable to calculate the actual strength and class of concrete for specimens aged 14 days.

The graph was constructed in order to visualize the shape and the size effect of specimens on concrete strength (Fig. 5):

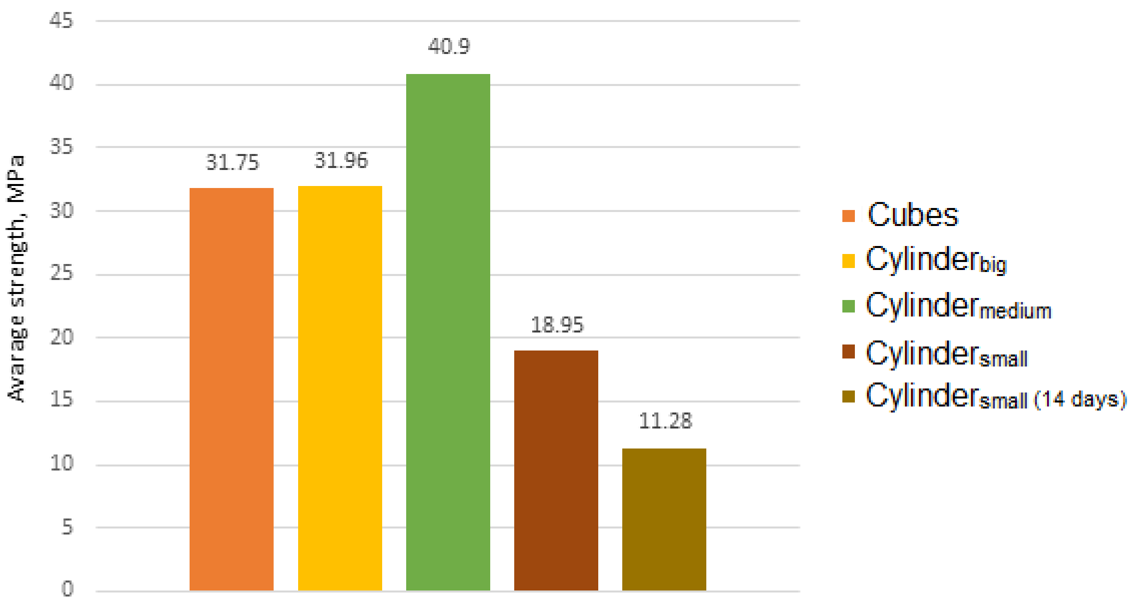

Figure 5. Summary graph of the average strength of all types of tested specimens

The generalized investigation results showed that the obtained data are consistent with the literature, namely that the compressive strength decreases with the specimen size increase. In the case of the smallest, non-standardized specimens (cylinders with 100 mm height and 50 mm diameter), the deviation of the compressive strength tests was higher compared to other specimens.

Conclusions. The size and shape effect (cubes with 150 mm face sizes and cylinders with diameters from 50 mm to 150 mm) of the specimens on the concrete compressive strength is investigated in this paper. Data obtained as the result of concrete specimens investigation on the test press are analyzed. Due to the formulas and data obtained after the investigation, the actual class of concrete strength is determined for all specimens. Based on the investigation results, the fracture diagrams for all types of control specimens are constructed. The results show that the laboratory measurements are consistent with the literature results, namely, that the compressive strength decreases with the specimen size increase. In the case of the smallest, non-standardized specimens (cylinders with 100 mm height and 50 mm diameter), the deviation of the compressive strength tests is higher compared to other specimens. The graph is presented in order to visualize the effect of specimen types and sizes on concrete strength. Using the results obtained in this paper for further scientific investigations is reasonable.

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ВПЛИВ ФОРМИ ТА РОЗМІРУ ЗРАЗКІВ НА МІЦНІСТЬ БЕТОНУ ЗА СТИСКУ

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Резюме. *Представлено результати дослідження впиву розмірів і типів зразків на показники міцності бетону. Дослідження міцності бетонних зразків, у вигляді кубів (150 мм х 150 мм х 150 мм) та циліндрів різних діаметрів (50 мм, 100 мм та 150 мм) та висоти (100 мм, 200 мм та 300 мм), за стиску проведено на випробувальній машині Matest з серво-приводним блоком керування Servo-Plus Evolution. Зразки кожного типу випробовували у кількості 3 штук. Контрольні зразки виготовляли згідно з такими співвідношеннями матеріалів, щоб бетон відповідав класу міцності С16/20. Усі зразки візуально оглядали на присутність у них дефектів, таких, як великі пори, відколи, усадочні тріщини. Після цього здійснено фактичні заміри усіх зразків, які показали мінімальні відхилення від запланованого розміру, що вважається допустимим. Для того, щоб перевірити достовірність результатів, після досліджень кожних типів зразків проведено розрахунок для визначення фактичної міцності та класу бетону. Для цього взято фактичні розміри граней і результати досліджень певної партії. Проаналізовано дані, отримані в результаті дослідження бетонних зразків на випробовувальному пресі. За допомогою формул і даних, отриманих після дослідження, визначено фактичний клас міцності бетону для всіх зразків. За результатами досліджень побудовано графіки руйнування всіх типів контрольних зразків. Результати експериментальних досліджень показали, що лабораторні вимірювання узгоджуються з літературними даними, а саме, що міцність на стиск зменшується зі збільшенням розміру зразка. У випадку найменших, нестандартизованих зразків (циліндри висотою 100 мм і діаметром 50 мм) відхилення випробувань на міцність на стиск було вищим порівняно з іншими зразками. Представлено графік для візуалізації впливу типів та розмірів зразків на міцність бетону.*

Ключові слова*: міцність, стиск, бетонні зразки, вплив форми та розмірів.*

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