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Effect of test specimen size on mechanical properties of shotcrete

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Professional paper

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Effect of test specimen size on mechanical properties of shotcrete

Laboratory testing of shotcrete installed in the primary support system of the Sveti Ilija Tunnel is described in the paper. The effect of the size of shotcrete specimens on the compressive strength and dynamic modulus of elasticity of the plain concrete and fibre reinforced concrete produced in-situ is analysed. The results are used to analyse suitability of estimating compressive strength based on the dynamic modulus of elasticity results.

Key words:
shotcrete, compressive strength, dynamic modulus of elasticity, size of test specimen

Stručni rad

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Utjecaj veličine ispitnog uzorka na mehanička svojstva mlaznog betona

U radu su opisana laboratorijska ispitivanja uzoraka mlaznog betona ugrađivanog u primarni podgradni sustav tunela Sveti Ilija. Promatran je utjecaj dimenzija ispitnih uzoraka mlaznog betona na tlačnu čvrstoću i dinamički modul elastičnosti običnog i mikroarmiranog betona izrađenog in situ. Pregledom dobivenih rezultata analizirana je i opravdanost procjene tlačne čvrstoće na temelju rezultata dinamičkog modula elastičnosti.

Ključne riječi:
mlazni beton, tlačna čvrstoća, dinamički modul elastičnosti, visina ispitnog uzorka

Fachbericht

Petar Matulić, Sandra Juradin, Elica Marušić, Ante Domazet

Einfluss der Probengröße auf die mechanischen Eigenschaften von Spritzbeton

In dieser Arbeit werden Laborversuche an Proben des in das primäre Unterbausystem des Tunnels Sv. Ilija eingebauten Spritzbetons beschrieben. Dabei wird der Einfluss der Dimensionen von Versuchsproben des Spritzbetons auf die Druckfestigkeit und das dynamische Elastizitätsmodul für herkömmlichen und mikroarmierten in situ hergestellten Beton betrachtet. Anhand der gegebenen Resultate wurde auch die Rechtfertigung von Abschätzungen der Druckfestigkeit aufgrund ermittelter Werte des dynamischen Elastizitätsmoduls analysiert.

Schlüsselwörter:
Spritzbeton, Druckfestigkeit, dynamisches Elastizitätsmodul, Höhe der Versuchsprobe

1. Introduction

As the compressive strength testing of hardened concrete is performed according to the HRN EN 12390-3 [1] on water-saturated cubic samples measuring 15 cm in length, or on cylindrical samples 15 cm in diameter and 30 cm in height, the question arises as to the compressive strength of samples in sizes deviating from standard ones. Namely, compressive strength values of the samples made of the same concrete but differing in size can vary considerably [2-5]. In these cases, appropriate coefficients are used to adjust the existing strength of samples to the strength of standard-size samples. The aim of this paper is to analyse the impact of different sizes of the samples of plain and fibre-reinforced concrete on the compressive strength and dynamic modulus of elasticity, and to compare relations of compressive strength of samples of various sizes obtained by shotcrete testing, with relations applying to standard concrete. The connection between compressive strength and dynamic modulus of elasticity will also be analysed, i.e. the possibility of estimating the compressive strength of shotcrete based on the dynamic modulus of elasticity measurement results will be explored. This method of estimating the concrete strength is highly practical as it enables simple determination of dynamic modulus using an ultrasound device that can easily be used and transported.

The problem of the impact of sample size on mechanical properties of concrete has been the subject of numerous studies throughout history. The first studies of this kind were conducted by Gonnerman in 1920 [6] who examined the compressive strength of cylinders measuring (3,8 x 7,6) cm and (15 x 30) cm in size, depending on the water-cement ratio. Based on test results, he concluded that smaller samples have a higher compressive strength compared to larger ones.

Harris and White [7] examined cylinders of varying height and diameter in order to determine the impact of sample size on compressive strength of concrete. The results of this study showed that the compressive strength of samples decreases with an increase in sample size. In addition to higher compressive strength values, smaller samples also exhibited a faster increase in strength.

Pang and Tsui [8, 9] observed the impact of sample size on concretes made with cement having a high initial strength and five different fractions of quartz sand. The cylinders measured (2,5 x 5) cm and (15 x 30) cm in size. They concluded that the compressive strength, as well as the standard deviation of strength, decreases with an increase in sample size.

Studies conducted by Neville [4, 10, 11] also show that the compressive strength, and its standard deviation, increase with a decrease in sample size. He presented concrete strength (P) as a function of sample volume (V), sample diameter (d), and h/d ratio, where h is the sample height. The impact of other factors on concrete strength was not taken into account due to the lack of relevant experimental data.

The author tried to establish a relationship between compressive strength of an arbitrary-sized sample and a 6-inch (15 cm) cube. The information on the concrete is the result of experimental work conducted by twelve different researchers. The relationship between the compressive strength of a sample and a 15-cm cube is shown below:

$$\frac{P}{P_o} = 0,56 + 0,697\left(\frac{d}{\frac{V}{6h} + h}\right) \quad (1)$$

where h and d are given in inches, while V is given in cubic inches.

Tests conducted by the Bureau of Reclamation [12] showed that, beyond a certain size, the compressive strength is no longer affected by an increase in sample size. This Bureau concluded that the decrease in strength with an increase in sample size is less pronounced in lean concretes.

According to Griffith [13], the likelihood of the weakest link occurrence increases with an increase in sample size. Fracture occurs due to formation of the largest micro-crack as a result of stress concentration under load. If a crack is observed as a local defect in a material due to concrete structure, then, statistically speaking, the occurrence of the crack may reasonably be expected primarily in larger samples, resulting in lower strength.

Krolo [14] examined the impact of non-homogeneity of concrete on the basic fracture-mechanics parameters for concrete samples of varying strength, maximum aggregate grain size, and sample size. Among other things, the author concluded that the fracture-mechanics parameter values *inter alia* depend on sample geometry.

The compressive strength of concrete is also influenced by friction [3] occurring between the test plates and samples. The friction prevents lateral spreading of sample, which results in a higher compressive strength of concrete.

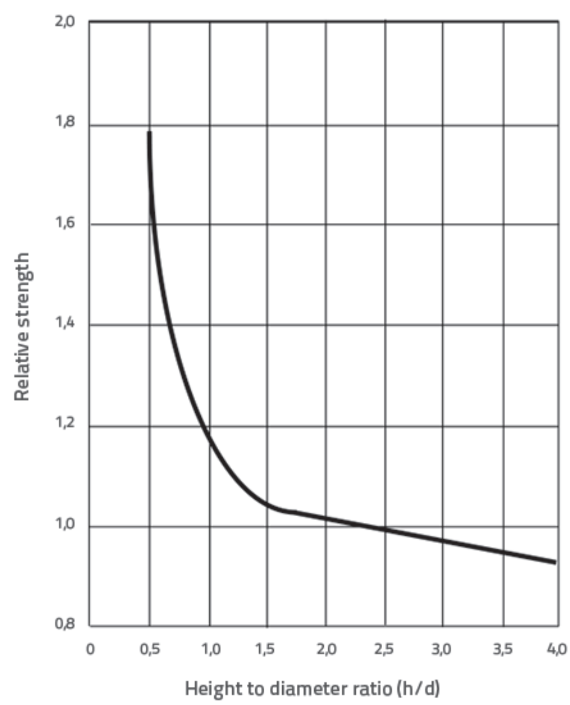

Figure 1. Influence of test-cylinder height to diameter ratio on relative strength [4]

The influence of cylinder size on concrete strength is shown in Figure 1. The strength of the samples having the height to radius of cylinder base ratio of *h/d* < 1.5 rapidly increases with a decrease in the ratio, while the strength of the samples having *h/d* > 1.5 rapidly decreases with an increase in the *h/d* ratio due to influence of thinness.

It should be noted that the strength of concrete deviates from the strength of standard size cylinders by merely 5 % in the *h/d* ratios ranging from 1.5 to 2.5.

Day [15] conducted extensive tests on the impact of the mould size and material on the compressive strength of concrete. Diameters of the test cylinders were 7.5, 10, and 15 cm, and the *h/d* ratio amounted to 2.0 for all samples. The moulds were made of cardboard and plastic. The average strength of the samples from the 15 cm plastic moulds was by approximately 1.4 MPa lower compared to the samples made using other mould types. The strength of the samples measuring 7.5 cm in diameter, originating either from the cardboard or plastic mould, was by approximately 1 MPa higher compared to the samples from larger moulds.

In [16] the same author processed over 8000 strength results and showed strength correlations for cylinders 100 (f_{100}) and 150 mm (f_{150}) in diameter, as obtained by other authors (Table 1).

Table 1. f_{100} and f_{150} correlation according to literature data [16]

Source	Suggested correlation	Strength range [MPa]
Aitcin et al.(1992)	$f_{100} = 1.16 \cdot f_{150} - 8.5$	80 - 100
Carrasquillo & Carrasquillo (1988)	$f_{100} = 0.93 \cdot f_{150}$	50 - 80
Date & Schnormeier (1984)	$f_{100} = 1.04 \cdot f_{150}$	< 35
Day & Haque (1993)	$f_{100} = f_{150}$	< 40
Day (1994) [15]	$f_{100} = f_{150}$	< 50
Forstie & Schnormeier (1981)	$f_{100} = f_{150}$	30 - 50
Forstie & Schnormeier (1981)	$f_{100} = f_{150};\ f_{100} > f_{150}$ za $f > 34.5$	< 50
Gonnerman (1925) [6]	$f_{100} = 1.01 \cdot f_{150}$	< 32
Lessard &Aitcin (1992)	$f_{100} = 1.05 \cdot f_{150}$	35 - 120
Malhotra (1976)	$f_{100} = (0.85$ do $1.05) \cdot f_{150}$	< 50
Cook (1989)	$f_{100} = 1.05 \cdot f_{150}$	< 90
Peterman & Carrasquillo (1983)	$f_{100} = (1.10$ do $1.15) \cdot f_{150}$	50 - 80
Janak (1985)	$f_{100} = 1.03 \cdot f_{150}$	< 56
Chojnacji & Read (1990)	$f_{100} = (1.02$ do $1.04) \cdot f_{150}$	58 - 97
Pistilli & Willems (1993)	$f_{100} = f_{150}$ (sulphur lid)	27 - 104
Pistilli & Willems (1993)	$f_{100} = f_{150}$ (polymer cartridge)	28 - 62
Carrasquillo & ost. (1981)	$f_{100} = 0.90 \cdot f_{150}$	30 - 80

Based on the data obtained from 22 studies (1168 results), he graphically presented the strength ratio using cylindrical samples 75 or 100 mm and 150 mm in diameter, Figure 2. As shown in this figure, the deviation of results from the line $f_{75/100} = f_{150}$ increases with an increase in strength. By analysing the variation coefficients obtained (Figure 3), the author concluded that, in the 20 to 60 MPa strength range, the strength variation coefficient for the smallest samples (75 mm) amounts to 5.2 %, while it amounts to approximately 3 % on larger samples. In the larger strength ranges, the coefficient of variation varies from 1.7 and 2.2 % for samples 100 and 150 mm in diameter. In conclusion, the author states: "There is strong evidence that one uses 100 mm plastic or steel molds, the strength obtained in the 20 to 100 MPa range is expected to be 5 % greater than that obtained using 150 mm molds. In the lower strength ranges, 20 to 60 MPa, for example, it may be acceptable to assume from practical perspective that strengths using 100 and 150 mm molds are equivalent; justification for such an assumption must be determined by standards authorities."

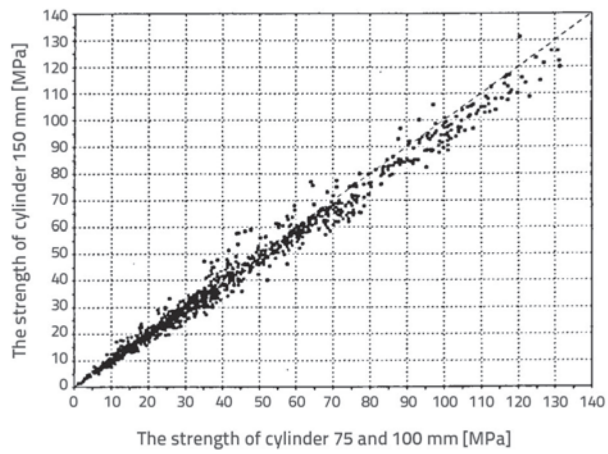

Figure 2. Overview of strength correlations for cylinders 100 and 150 mm in diameter [16]

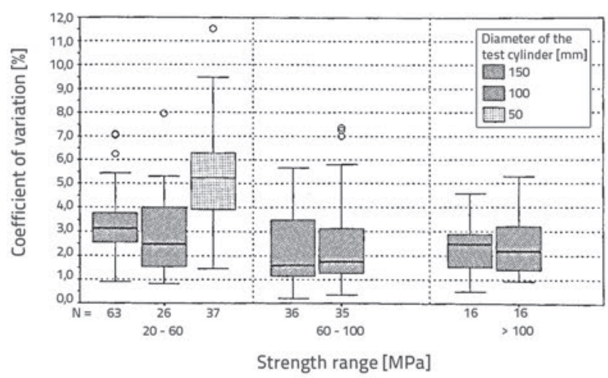

Figure 3. Dependence of variation coefficient on cylinder strength and diameter [16]

Vandergrift and Schindler [17] attempted to determine the strength conversion factor for samples 100 and 150 mm in diameter, and carried out the statistical processing of results. The results are presented in Table 2.

Table 2. Conversion factor *k*, $f_{100} = k \cdot f_{150}$ [17]

Strength range [MPa]	Minimum	Mean value	Maximum
30	0.94	1.08	1.19
40	0.88	0.97	1.03
60	0.68	0.83	0.93
All strenghts	0.68	0.96	1.19

According to [18] "The 100 mm x 200 mm (4-in. x 8-in.) cylinders are easier to cast, require less material, weigh considerably less than 150 mm x 300 mm (6-in. x 12-in.) cylinders and require less storage space for curing". "The standard deviation and coefficient of variation of 100 mm (4-in) cylinders is slightly higher or similar to that for 150 mm (6-in) cylinders" [19].
As a general conclusion from these studies, it can be stated that the strength of concrete is truly a function of the size of test samples. The increase of the test sample size results in the concrete strength decrease, and in the decrease of the standard deviation and coefficient of strength variation. However, the impact of concrete strength is nevertheless limited so that, after a certain value, a further increase in sample size no longer affects the decrease in compressive or tensile strength of concrete.

2. Preparation and testing of samples

The testing was conducted using plain concrete and fibre-reinforced shotcrete samples from the primary support system of the St. Ilija Tunnel. The samples were taken from the sprayed panels constructed *in situ*.

Figure 4. Primary support system in St. Ilija Tunnel [24]

Table 3. Composition and required properties of concrete

Composition of concrete		
Concrete components	**Plain shotcrete** [kg]	**Fibre-reinforced shotcrete** [kg]
Cement – CEM II/B (S-LL) 42.5 N	480	475
Aggregate - crushed		
0-4 mm	1394	1428
4-8 mm	246	252
Admixtures		
D1 – accelerator (alkaline base)	19.2	19
D2 – steel fibres 35/0.65		30
D3 – superplasticizer (naphthalene sulphate base)		1.75
Water	220	210
w/c	0.45	0.44
Total	2340	2395
Required properties of concrete		
Compressive strength class	25/30	25/30
Exposure class	XC1	XC1
Consistency (slump)	S2 (50 - 90 mm)	S3 (100 – 150 mm)

The St. Ilija Tunnel (Figure 4) connects the village of Rastovac near Zagvozd on the northern side with Bast near Baška Voda on the southern side, and constitutes a significant structure along the road connecting the A1 motorway at Zagvozd to the D8 road. The designed length of the tunnel is 4.1 km. Cylindrical test samples measuring 5 cm in diameter were taken from the sprayed panels by drilling, and then sawn to the height of 15 cm. A total of 133 samples were taken. The sample height amounted to 15 cm for 129 samples, 10 cm for 3 samples, and 5 cm for 1 sample. Out of the total number of samples, 89 samples were made of plain shotcrete, while 44 samples were made of fibre-reinforced shotcrete. The flatness of samples, required by HRN EN 12390-1 [20] was achieved by grinding the bases, with special attention paid to the verticality of the generating line to the cylinder base, and dimensions were obtained by averaging three measurements. The samples were kept in water at 20 ± 2 °C (Figure 5) until full saturation, as determined by measuring their mass.

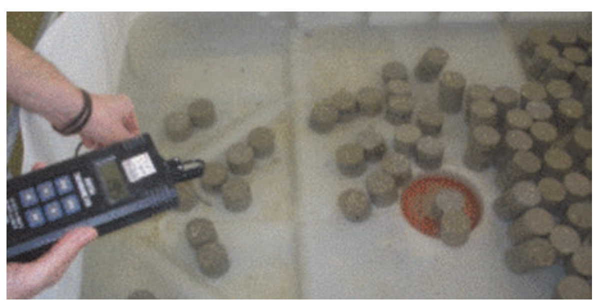

Figure 5. Keeping samples in water until full saturation [24]

The time needed for ultrasound waves to pass through test samples was measured using an ultrasound device with cylindrical probes with a nominal frequency of 54 Hz. The velocity of ultrasound wave transfer was calculated based on the measured time and sample height, in accordance with HRN EN 12504-4:2004 [21]. As the testing lasted several days, before the start of the measurement, the time of wave transfer through a standard cylinder tested by the test device manufacturer was determined, after which the adjustments of all results were made. The dynamic modulus of elasticity was calculated according to the formula

$$E_{din} = v^2 \cdot \rho \cdot \frac{(1+\upsilon)\cdot(1-2\cdot\upsilon)}{(1-\upsilon)} \cdot 10^9 \qquad (2)$$

where:
E_{din} - the dynamic modulus of elasticity [GPa]
v - ultrasound wave velocity [m/s]
ν - Poisson's ratio
ρ - sample density [kg/m^3].

As the Poisson's ratio values may vary from 0.15 to 0.25, the value of 0.20 was adopted for the purposes of this testing. The samples were wiped immediately prior to testing, and the bases were coated with an agent, to ensure better conductivity of ultrasound waves.
After determining the dynamic modulus of elasticity on samples 15 cm in height, the samples were sawn apart to obtain two samples measuring 5 cm and 10 cm in height, respectively. The process of grinding was repeated so as to achieve the required flatness. After determining the dynamic modulus of elasticity, the exact sizes of sawn samples were defined to enable compressive strength testing in accordance with HRN EN 12390-3 standards for hardened concrete testing, and HRN EN 12504-1 [22] standards for testing concrete in structures, as referred to in HRN EN 14488-1 [23]. The testing machine having an accuracy class of 1, calibrated in the range of 30 kN to 300 kN, was used in this testing. The samples were aligned with an accuracy of 1 % of the sample size, and the load application rate was 0,6 MPa/s.
The compressive strength was obtained according to the equation (3):

$$f_c = \frac{F}{A_c} \qquad (3)$$

where:
f_c - compressive strength of concrete [MPa]
F - load at fracture [N]
A_c - cross-sectional area perpendicular to the direction of load [mm^2].

Figure 6. Compressive strength testing [24]

Table 4. Test results with corresponding statistical sizes

Dynamic modulus of elasticity		E_{MIN} [GPa]	E_{MAX} [GPa]	E_{SRED} [GPa]	V [%]	σ [GPa]
Plain concrete	h = 15 cm	30.1	44.8	37.3	9.23	3.44
Fibre-reinforced concrete		29.9	45.6	40.8	7.87	3.21
Plain concrete	h = 10 cm	31.3	43.2	38.3	7.70	2.95
Fibre-reinforced concrete		31.0	46.3	41.5	7.21	2.99
Plain concrete	h = 5 cm	27.4	39.2	34.4	7.85	2.70
Fibre-reinforced concrete		30.3	42.1	38.0	6.62	2.51
Comprressive strength		f_{MIN} [MPa]	f_{MAX} [MPa]	f_{SRED} [MPa]	V [%]	σ [MPa]
Plain concrete	h = 5 cm	22.9	64.3	42.3	22.70	9.60
Fibre-reinforced concrete		28.3	61.9	50.9	16.44	8.36
Plain concrete	h = 10 cm	17.9	57.8	35.3	24.72	8.74
Fibre-reinforced concrete		20.1	52.5	40.5	16.89	6.84

Table 5. F and t-test results

Rations	F_0; F	t_0; t	F-test (α = 0,05)	t-test (α = 0,05)	Mean value	Variance	Stand. deviation
σ/E for h = 5 cm, plain concrete	F_0 = 1.28	t_0 = 10.07	no significant stat. differences between the variances	significant stat. differences between arithmetic means	1,22	0,0449	0,2119
σ/E for h = 10 cm, plain concrete	F = 1.43	t= 1.96			0,92	0,0351	0,1874
σ/E for h = 5 cm, reinforced concrete	F_0 = 1.88	t_0 = 11.15	significant stat. differences between the variances	significant stat. differences between arithmetic means	1,33	0,0297	0,1724
σ/E for h = 10 cm, reinforced concrete	F = 1.67	t = 1.96			0,97	0,0158	0,1258
σ/E for h = 5 cm, plain concrete	F_0 = 1.51	t_0 = 3.14	no significant stat. differences between the variances	significant stat. differences between arithmetic means	1,22	0,0449	0,2119
σ/E for h = 5 cm, reinforced concrete	F = 1.58	t = 1.96			1,33	0,0297	0,1724
σ/E for h = 10 cm, plain concrete	F_0 = 2.21	t_0 = 1.76	significant stat. differences between the variances	no significant stat. differences between arithmetic means	0,92	0,0351	0,1874
σ/E for h = 10 cm, reinforced concrete	F = 1.58	t = 1.96			0,97	0,0158	0,1258
$\sigma_{h = 5 cm}/\sigma_{h = 10 cm}$, plain concrete	F_0 = 1.48	t_0 = 1.89	no significant stat. differences between the variances	no significant stat. differences between arithmetic means	1,21	0,0243	0,1557
$\sigma_{h = 5 cm}/\sigma_{h = 10 cm}$, reinforced concrete	F = 1.58	t = 1.96			1,26	0,0164	0,1281
$E_{h = 5 cm}/E_{h = 10 cm}$, plain concrete	F_0 = 1.35	t_0 = 1.76	no significant stat. differences between the variances	no significant stat. differences between arithmetic means	0,9	0,0029	0,0535
$E_{h = 5 cm}/E_{h = 10 cm}$, reinforced concrete	F = 1.58	t = 1.96			0,92	0,0021	0,046
$E_{h = 5 cm}/E_{h = 15 cm}$, plain concrete	F_0 = 1.1	t_0 = 0.85	no significant stat. differences between the variances	no significant stat. differences between arithmetic means	0,93	0,0022	0,0469
$E_{h = 5 cm}/E_{h = 15 cm}$, reinforced concrete	F = 1.58	t = 1.96			0,93	0,0020	0,045
$E_{h = 10 cm}/E_{h = 15 cm}$, plain concrete	F_0 = 1.43	t_0 = 1.32	no significant stat. differences between the variances	no significant stat. differences between arithmetic means	1,03	0,0020	0,0452
$E_{h = 10 cm}/E_{h = 15 cm}$, reinforced concrete	F = 1.58	t = 1.96			1,02	0,0014	0,0373
$E_{h = 5 cm}/E_{h = 15 cm}$, plain concrete	F_0 = 1.1	t_0 = 15.15	no significant stat. differences between the variances	significant stat. differences between arithmetic means	0,93	0,0022	0,0469
$E_{h = 10 cm}/E_{h = 15 cm}$, plain concrete	F = 1.43	t = 1.96			1,03	0,0020	0,0452
$E_{h = 5 cm}/E_{h = 15 cm}$, reinforced concrete	F_0 = 1.43	t_0 = 9.72	no significant stat. differences between the variances	significant stat. differences between arithmetic means	0,93	0,0020	0,045
$E_{h = 10 cm}/E_{h = 15 cm}$, reinforced concrete	F = 1.67	t = 1.96			1,02	0,0014	0,0373
$E_{h = 5 cm}/E_{h = 10 cm}$, plain concrete	F_0 = 1.32	t_0 = 3.37	no significant stat. differences between the variances	significant stat. differences between arithmetic means	0,9	0,0029	0,0535
$E_{h = 5 cm}/E_{h = 15 cm}$, plain concrete	F = 1.43	t = 1.96			0,93	0,0022	0,0469
$E_{h = 5 cm}/E_{h = 10 cm}$, reinforced concrete	F_0 = 1.05	t_0 = 1.75	no significant stat. differences between the variances	no significant stat. differences between arithmetic means	0,92	0,0021	0,046
$E_{h = 5 cm}/E_{h = 15 cm}$, reinforced concrete	F = 1.67	t = 1.96			0,93	0,0020	0,045

3. Presentation and discussion of test results

A series of test results was established for 89 samples of plain concrete, and 43 samples of fibre-reinforced shotcrete. Total test results are presented in Table 4. Statistical *F* and *t*-tests (Table 5) were carried out and the correlation analysis was made to determine correlation of the series under study.

3.1. Compressive strength ratio for different size samples

Table 4 shows that compressive strength results for plain and fibre-reinforced shotcrete vary to a great extent. The reason for this is the specific manner of placing shotcrete *in situ,* where it is difficult to achieve a uniform concrete quality by means of spraying due to the amount of rebound, which in some cases may amount to as much as 40 % of the initial mixture. Regardless of the range of the results obtained, samples are considered to be representative because the compressive strength ratio of the samples 5 and 10 cm in height, which are made of the same shotcrete sample 15 cm in height is observed. The mean compressive strength ratio for plain shotcrete samples 5 cm in height, compared to the samples 10 cm in height, amounts to 1.20, while this ratio amounts to 1.26 for the fibre-reinforced shotcrete. It is stated in HRN EN 13791:2007 [25] that the compressive strength of cylinders with the height to diameter ratio of about 1 corresponds to the compressive strength of the cube of side 15 cm. According to HRN EN 206-1:2006 [1, 26], characteristic compressive strength of concrete is defined as the compressive strength of a 15 cm cube, or a cylinder with a diameter of the base of 15 and a height of 30 cm. It is specified in this standard that the strength ratio of these two solids is provided in the definition of the class. For the compressive strength values of the tested samples ranging from class C16/20 to class C55/67, this ratio varies from 1.20 to 1.25. It is concluded that the compressive strength ratio of the samples, with the size ratio of 1:1 and the compressive strength of the samples with the base diameter to height ratio of 1:2 obtained by shotcrete testing, corresponds to the compressive strength of the tested solids as defined by standards for normal concrete.

Test results showed that the compressive strength of fibre-reinforced shotcrete samples is by 15 to 20 % higher compared to the plain shotcrete with lower dissipation of results, which is confirmed by the value of the coefficient of variation. For the above ratio, a correlation link has been established (Figure 7) that measures the degree of intensity of stochastic relations by means of correlation coefficients, including graphic representation and the intensity and direction of the correlation between the observed variables.

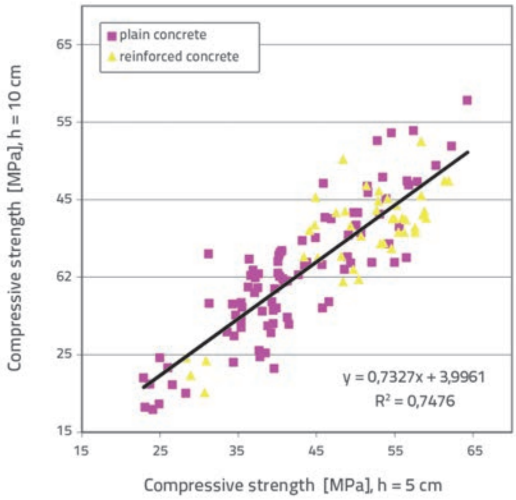

Figure 7. Regression line of compressive strengths for samples 5 and 10 cm in height (*R* = 0, 86)

The correlation coefficient of R=0,86 indicates a very high correlation between the considered sizes [27]. The F and t-test results for compressive strength of the plain and fibre-reinforced shotcrete cylinders 5 and 10 cm in height showed no significant statistical difference between the surveyed sets, i.e. the plain and fibre-reinforced concrete results can be considered together (Table 5).

3.2. Ratio of dynamic modulus of elasticity for different size samples

The highest mean dynamic modulus of elasticity for the plain shotcrete and fibre-reinforced shotcrete was registered in samples 10 cm in height. The ratio of dynamic modulus of elasticity of samples 5 cm in height, and samples 10 cm or 15 cm in height, amounts to 0.9. The ratio of dynamic modulus of elasticity of samples 10 cm and 15 cm in height amounts to 1.03. Thus the samples of less than 10 cm in height have a higher compressive strength, but their dynamic modulus of elasticity is lower. A probable cause of this phenomenon may lie in the nature of destructive and non-destructive test methods. Local defects are more likely to occur in larger size samples, and these defects are more readily registered with the destructive method for compressive strength testing, compared to the non-destructive method for measuring dynamic modulus of elasticity. It is assumed that that the velocity of ultrasound waves is less affected in larger samples encountering a defect compared to smaller samples, since the same defect extends the path travelled by the ultrasound wave in a shorter sample, thus further reducing the speed of the wave and the dynamic modulus of elasticity as compared to a longer sample. The obtained results showing that the value of the dynamic modulus of elasticity no longer reduces with an increase in sample size beyond 10 cm in height, correspond to the findings made in the scope of previous research conducted by Bungey [28, 29]. Based on his research, the author suggested "minimum path lengths of 100 and 150 mm for concrete with maximum aggregate sizes of 20 and 40 mm, respectively " [28].

As in this paper the test concretes were built with the maximum aggregate grain size of *D* = 8 mm, the minimum recommended sample height of 10 cm may be applied for concretes with a smaller maximum aggregate grain size.

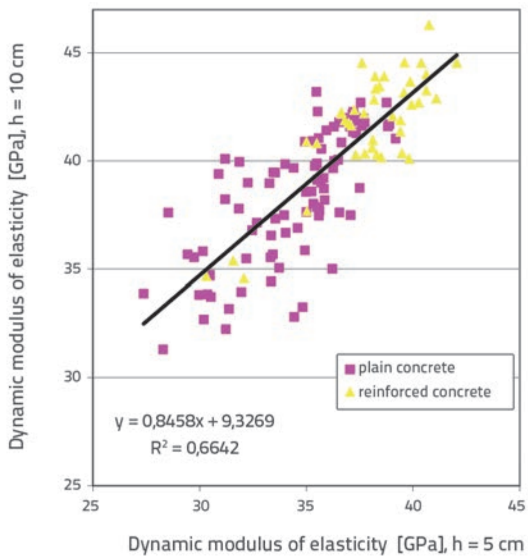

Figure 8. Regression line of dynamic modulus of elasticity for samples 5 and 10 cm in height (*R* = 0,81)

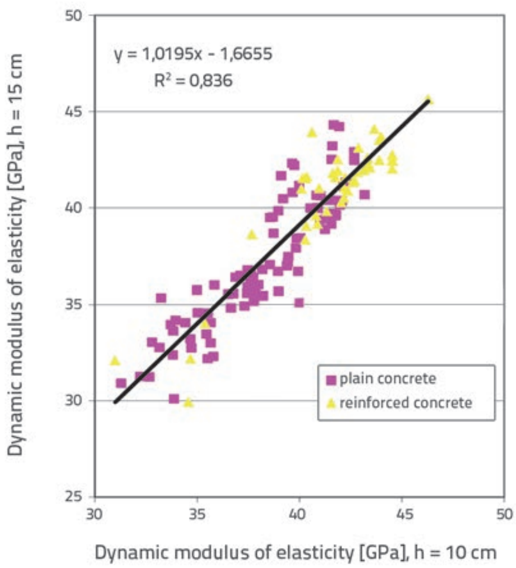

Figure 9. Regression line of dynamic modulus of elasticity for samples 10 and 15 cm in height (*R* = 0,91)

A relationship, also presenting a very high correlation of the observed sizes, was established for the observed ratios, as shown in Figures 8, 9, and 10. In this analysis, a unique set was formed from plain and fibre-reinforced concrete samples according to the F and t-test results (Table 5).

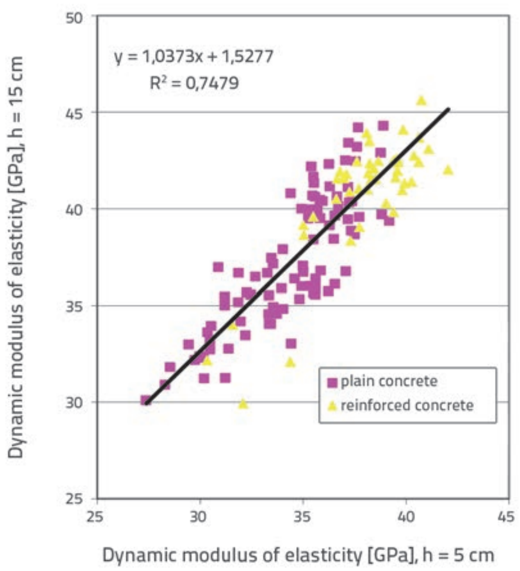

Figure 10. Regression line of dynamic modulus of elasticity for samples 5 and 15 cm in height (*R* = 0,86)

Regarding the ratio of dynamic modulus of elasticity of samples with a height of 5 and 10 cm, 5 and 15 cm, and 10 and 15 cm, for both types of the tested shotcretes, as well as the ratio of dynamic modulus of elasticity of the height of 5 cm and 10 cm in relation to the samples of fibre-reinforced concrete with the height of 5 cm and 15 cm, *F* and *t*-test results showed no significant statistical difference (Table 5).

3.3. Connection between compressive strength and dynamic modulus of elasticity for different size samples

One of the tasks of the paper, i.e. of the analysis of test results for shotcrete samples, was also to establish a connection between the compressive strength of concrete and the dynamic modulus of elasticity. The compressive strength of concrete to dynamic modulus of elasticity ratio is defined by the regression line. A better connection between the observed properties of concrete, compared to the analysis based on the calibration curve defined by the HRN EN 13791:2007 [30] standard, can thus be obtained.

The correlation coefficients of test results suggest that a significant correlation exists between the compressive strength and dynamic modulus of elasticity (Figure 11 and Figure 12).

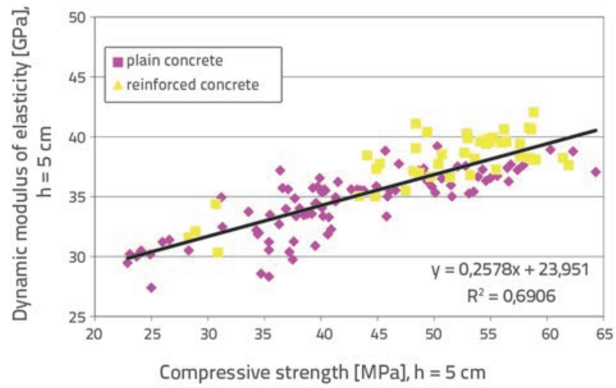

Figure 11. Regression line of dynamic modulus of elasticity and compressive strength of samples 5 cm in height (*R* = 0.83)

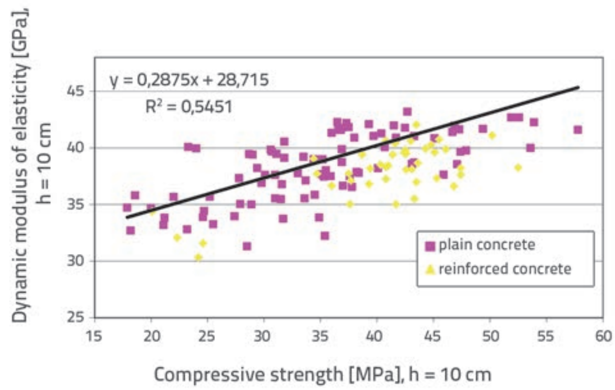

Figure 12. Regression line of dynamic modulus of elasticity and compressive strength of samples 10 cm in height (*R* = 0.74)

However, one should be careful when using this ratio in the assessment of compressive strength since the regression line has a small inclination to the compressive strength axis. The result is that even a small error when measuring dynamic modulus of elasticity may result in a significant change in the compressive strength of shotcrete. Thus for the test samples 5 cm in height, a 1 GPa change in dynamic modulus of elasticity corresponds to the change of 3.9 MPa in compressive strength, while this change amounts to 3.5 MPa in test samples 10 cm in height. Therefore, when assessing the compressive strength based on the dynamic modulus of elasticity results, one should be aware of the uncertainty associated with this assessment.

4. Conclusion

The analysis of results shows that the compressive strength ratio of plain shotcrete samples 5 cm and 10 cm in height, without the addition of fibres, amounts to 1.20, while this ratio in fibre-reinforced concrete samples amounts to 1.26. The results confirm the relationships of compressive strength of samples with the size ratio of 1:1, and the samples with the base diameter to height ratio of 1:2, as defined in standards HRN EN 13791:2007 and HRN EN 206-1:2006. The samples with fibres and superplasticisers result in a greater homogeneity, and so the obtained compressive strength values show less dissipation. The coefficient of variation is lower in lower-height samples, which points to a higher likelihood of encountering local defects in bigger samples. Unlike compressive strength, the samples 5 cm in height, i.e. the samples with the base diameter to height ratio of 1:1, have an approximately 10 % lower dynamic modulus of elasticity compared to the samples 10 cm and 15 cm in height, having approximately the same dynamic modulus of elasticity. Thus, the change in sample size affects the change in compressive strength and dynamic modulus of elasticity differently, which may be interpreted by the difference in the nature of non-destructive and destructive test methods. The results obtained confirm the current recommendation for the minimum sample height of 10 cm for concrete, and this research established that this restriction in sample height also applies for concrete with a smaller maximum grain size. The coefficient of variation of the dynamic modulus of elasticity is lower in samples containing fibres and superplasticisers.

Tests have confirmed that a certain correlation exists between the compressive strength and dynamic modulus of elasticity results for shotcrete samples 5 and 10 cm in height, and formulas obtained by correlation analysis for assessing the compressive strength based on the dynamic modulus of elasticity results. However, when assessing the compressive strength based on dynamic modulus of elasticity results obtained via an ultrasonic device, one should be aware of the uncertainty of the method, since a small error in measuring the dynamic modulus of elasticity causes a significant error in the assessment of the compressive strength of shotcrete. The resulting connection may apply to the concrete used in the primary support system of the tunnel, while for other types of concrete it may serve as a rough estimate only. It should also be noted that the tests were performed on water-saturated samples, and so certain deviations may occur in the use of the connection between the compressive strength and dynamic modulus of elasticity on some dry samples.

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