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Determination of the Influence of Cylindrical Samples Dimensions on the Evaluation of Concrete and Wall Mortar Strength Using Ultrasound Method

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Abstract

The issue of samples shape and size effect on the destructive strength of concrete returns from time to time because the compliance of conversion factors proposed by various authors is not satisfactory. Modern drilling equipment encourages to take samples from the structure and to conduct tests of concrete compressive strength based on the destruction of cylinders. This paper presents the ultrasound test methodology for determination of ‘d’ conversion factor from samples obtained, e.g., from structure for strength determined on other samples. First, the velocities of longitudinal ultrasound waves were reduced to a fixed base because samples of various sizes from Ø4 to Ø32 cm were tested. Regression curves for the tested samples were determined, separately for each size. Based on these, for various ultrasound velocities and various sizes of samples strengths and relations between strengths was calculated. Formulas were given, which allow to convert the strength from sample of any diameter to the different one. The example of ultrasound testing method for the evaluation of mortar strength in joints between bricks was also presented.

Keywords: concrete, ultrasounds, bore-holes, cylindrical samples, size, strength, walls, mortar.

1. Introduction

Always when it is required to analyse the condition of an existing structure, whether with respect to safety or the quality of the material used, it is necessary to define certain technical or physical parameters, most often compressive strength, porosity or moisture are needed. Testing of these parameters always encounters some difficulties, even though some methods are more or less specified in standards, e.g. [1, 2, 3]. Usually we have two groups of methods at our disposal: destructive ones consisting in taking samples of material, most frequently by making bore-holes, and non-destructive methods [4]. Among them, surface methods are used based on measurement of elastic reflection or plastic deformation practical application of which can be found in [5, 6], and ultrasound methods based on measurement of the time of transfer between two heads of longitudinal wave C_L or surface wave C_R [7, 8, 9, 10, 11].

In the destructive method, a serious problem is conversion of, for example, compressive strength from extracted cylindrical samples with different diameters for standard samples or in the case of mortars for beams with 4x4cm cross-section [12]. In the non-destructive, e.g. impact methods, a relatively high thickness of tested element is necessary – 10 cm and distance from the edge of 2–3 cm [13]. Testing of mortar between bricks using such method is practically unfeasible.

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The ultrasound method is very good when there is easy access to two opposite surfaces (direct transmission method), other transmission methods lose considerable accuracy [14].

As a result of this research, certain principles of conducting measurements and developing results were established, that allows to improve the accuracy of any determined parameters, significant extension of the scope of possible applications, and in the case of ultrasound tests, considerable simplification of measurement methodology. Sclerometric methods are easier to use than the classic ultrasound method, but this need not always be the case. Opportunities provided by the surface ultrasound method are much broader than in classic sclerometric methods, and at the same time the measurement method is as simple as the reflection method, for example with use of the Schmidt sclerometer.

2. The issue of converting concrete strength determined from samples with different diameters

Cores are often drilled and then tested when the strength of concrete in structures is doubted. Generally, samples with dimensions which are regarded as standard (currently cylinders Ø = 15 cm, h = 30 cm) cannot be extracted from the structure. Sometimes, the maximum diameter of the cylinder which can be extracted from between reinforcement bars is only 4÷8 cm. Similarly, the maximum fraction of aggregate grains limits the dimensions of any extracted samples [15, 16, 17]. If the cores are tested to shape the actual concrete strength, the test results should be carefully evaluated since there are a number of factors affecting the core strength [18].

Dependencies between the compressive strength of concrete determined using samples of different sizes were tested in the second half of the 20th century. Various researches ([19], Table 1) obtained various conversion factors. Usually the prevailing opinion was that the bigger the cylindrical sample, the lower the compressive strength determined as a relation of destructive force P to the sample surface S (Table 1).

Table 1. Comparison of conversion factors for various types of cubic and cylindrical samples according to various authors and standards [20]

Author or standard	Dimensions of sample with strength f_1	Dimensions of sample with strength f_2	Conversion factor $d = f_1/f_2$
PN-75/8-06250	15x15x15	10x10x10	0.9
	15x15x15	20x20x20	1.05
	15x15x15	Ø15x30	1.25
	15x15x15	Ø16x16	1.15
Price	Ø10x20	Ø25x50	1.04
Thaulow	Ø10x20	Ø25x50	1.025
Gonnerman	Ø10x20	Ø25x50	1.01
Tucker	Ø10x20	Ø25x50	1.00
Hamoda	Ø15x30	Ø25x50	1.10
Paszkowski	Ø16x16	Ø19,6x19,6	1.10
	Ø16x16	Ø8x8	0.85
Kuczyński	Ø16x16	Ø19,6x19,6	1.12
	Ø16x16	Ø8x8	0.87
Rusch	Ø10x10	20x20x20	1.20
	Ø30x30	20x20x20	0.85
Hernandez	Ø15x15	20x20x20	0.92
DIN1048	Ø10x10	20x20x20	1.15
L'Hermite	Ø5x5	15x15x15	0.94
	Ø10x10	15x15x15	0.97
	Ø20x20	15x15x15	1.02
	Ø30x30	15x15x15	0.95
	Ø40x40	15x15x15	0.74
Stawiski	Ø10x10	15x15x15	1.00
	Ø8x8	15x15x15	1.01

It could be concluded from the L'Hermite test that cube samples both bigger and smaller than cubes 15×15×15 cm show lower strengths. Only cubes 20×20×20 cm are slightly stronger than the 15s, that is, in these tests these were the strongest samples. In the quoted tests, only the shape (cylinder, cube) and dimensions of samples were taken into account. It is assumed that the tested dependency is not a single-parameter one. It is known that friction forces between the tested concrete and the steel surface of the pressure plate have considerable influence on compressive strength tested in the strength machine.

They depend on the friction factor and pressing force. The stronger the concrete, the higher the pressing force at the moment of destruction, therefore the higher the friction force. For weaker concretes, friction forces are lower and their effect in counteracting destruction will be smaller. How big are this forces? Let's compare them using the sample Ø = h = 4 cm, with the bottom surface of 12.5 cm^2:

- Concrete with strength 10 MPa – destructive force S = 12.5 kN – friction force T = 7.5 kN;
- Concrete with strength 20 MPa – destructive force S = 25.0 kN – friction force T = 15 kN;
- Concrete with strength 40 MPa – destructive force S = 50.0 kN – friction force T = 30 kN.

As the size of the sample increases, the plane in which friction force counteracts destruction of the concrete moves away from the surface in the middle of the height where destruction begins. In short, the factor for conversion of compressive strength from smaller to bigger samples or vice versa should be made dependent on at least two parameters: sample size and concrete strength

In order to try to eliminate apparent dispersions, using mean values to hide it, the assumption was accepted that the comparison will concern correlation curves established between the velocity of the longitudinal ultrasound wave and concrete strength. By determining correlation curves between impulse velocity and strength for samples of various sizes, it is possible to compare strengths from various curves for low or high velocity, that is with low strength or high strength. In order to ensure that this concept brings about an expected result, measurements of velocity on various samples (on different routes) cannot be burdened with systematic errors. For examples, it is necessary to eliminate geometric dispersion that is encountered, if the assumptions concerning an unlimited unit (small samples) are not fulfilled.

3. Description of tests conducted and results obtained

Tests were conducted on cylindrical samples with diameters of Ø4, Ø8, Ø16 and Ø32 cm. The range of diameters accepted covers all of bore-hole diameters encountered. The height of the samples was equal to their diameters. Concretes were designed using three types of aggregates 0–5 mm, 0–10 mm and 0–20 mm. In order to obtain various strengths, the samples were tested after 7, 14 and 28 days of aging. Compressive strengths were obtained from the following ranges: samples Ø = h = 4 cm – f_c = 15÷37 MPa, samples Ø = h = 8 cm – f_c = 15÷32 MPa, samples Ø = h = 16 cm – f_c = 15÷36 MPa, samples Ø = h = 32 cm – f_c = 13÷31 MPa. All samples from disassembling until the moment of testing were stored in an air-conditioned chamber, at a temperature of 18–20 °C and moisture of 90–95%. In spite of this, the moisture of the small samples was much lower than of the biggest samples. Tests regarding the time of transmission of an ultrasound impulse through the samples, along their height, so on routes from 40 mm to 320 mm were carried out directly before the destructive tests in the strength testing machine. 40 kHz heads was used for the measurement. For correlation analyses, concretes with various grain structures were combined in a separate set for each sample size, each containing 36 pieces. In total, 144 cylindrical samples were tested.

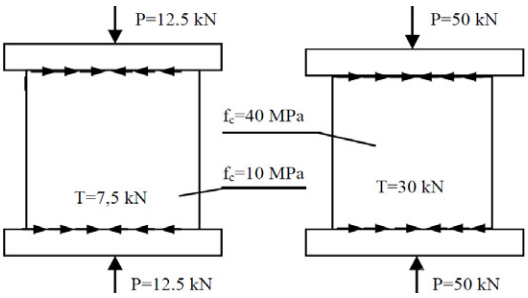

Fig. 1. Friction force T between concrete and steel plate in cylindrical sample Ø = h = 4 cm

The results obtained show that the velocities of the longitudinal ultrasound wave were the lowest in the smallest samples, and the highest in the samples of Ø32 mm (Fig. 1). One of the reasons for the observed heterogeneity was the dimension of the sample and geometric dispersion connected with it. In many publications, it was indicated that the length of the route may have an effect on the determined velocity [7, 21, 22]. Therefore, various route lengths were converted to one 80 mm route. Conversion factors were established by dividing mean velocity for all samples with a given length by mean velocity for samples with the length of 80 mm. Dependency with the following formula was obtained:

$$k = 1.2553x - 0.0478 \tag{1}$$

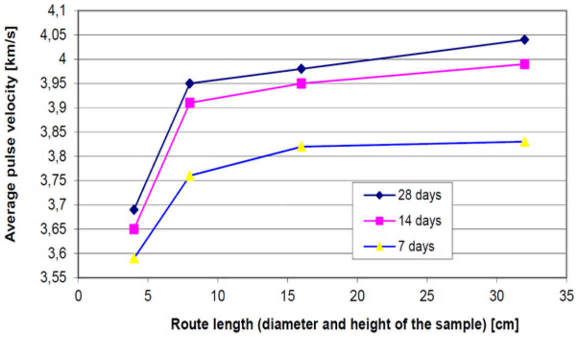

Fig. 2. Dependence of mean ultrasound velocity on sample sizes.

from which the conversion factor k for this concrete can be calculated, transforming velocities to the base of 80 mm (Fig. 3). Corrected velocities for one series are shown in Fig. 4.

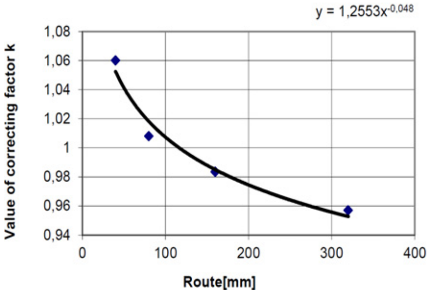

Fig. 3. Factor converting velocities of ultrasounds determined on routes with various lengths to a common base, here assumed as 80 mm

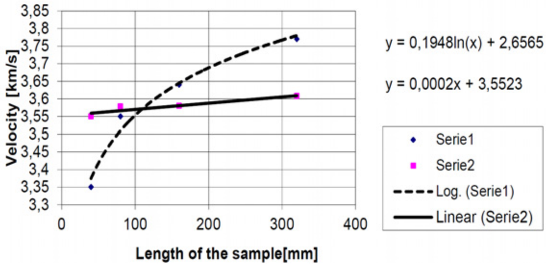

Fig. 4. Comparing velocities of ultrasounds for samples from one of the series of tests before the correction (Serie 1) and after the correction (Serie 2)

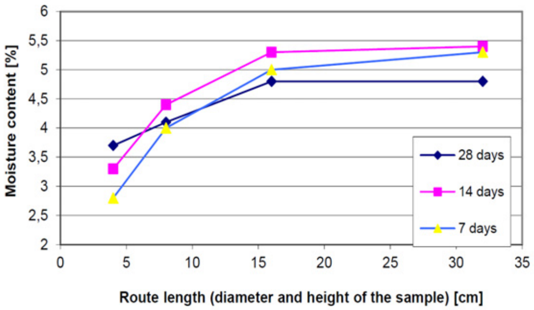

Fig. 5. Mean moisture of concrete in samples with various dimensions for the series using the finest aggregate

Mean velocities in samples with different dimensions are not yet identical but differences are at this point very small, that is 3.55 km/s in samples Ø4 cm and 3.61 km/s in samples Ø32 cm. Total compliance of mean results was obtained when a correction was made taking into account the different moisture of small and large samples (Fig. 5).

After conversion of all velocities to a common base, it can be assumed that only the shape and size of the sample will have an effect on the correlation dependency between the velocity of ultrasounds and strength. Therefore, correlation curves were determined separately for each of the sample sizes. The dependencies sought were approximated using a power function. The following formulas were obtained:

$$\text{for cylinders Ø 4 cm} \quad f = 0{,}0233x^{5{,}1967} \quad [\text{MPa}] \tag{2}$$

$$\text{for cylinders Ø 8 cm} \quad f = 0{,}0201x^{5{,}3381} \quad [\text{MPa}] \tag{3}$$

$$\text{for cylinders Ø 16 cm} \quad f = 0{,}0118x^{5{,}7562} \quad [\text{MPa}] \tag{4}$$

$$\text{for cylinders Ø 32 cm} \quad f = 0{,}0228x^{5{,}1111} \quad [\text{MPa}] \tag{5}$$

From each of the given curves, concrete strength was calculated for velocities 3.6; 3.7; 3.8; 3.9 km/s. Results were summarized in Table 2. Then relations of concrete strengths determined on samples with various sizes were calculated which are conversion factors (Table 2).

Table 2. Factors for conversion of strengths from samples with diameter x to strengths according to samples 4 cm, 8 cm, 16 cm and 32 cm

Sample diam. Ø [cm]	Formula No.	Calculated strength [MPa] For velocities C_L [km/s]				Conversion factor d											
						Ø4/ Øx = d			Ø8/ Øx = d			Ø16/ Øx = d			Ø32/ Øx = d		
						STRENGTH [MPa]											
		3.6	3.7	3.8	3.9	18	24	27	18	24	27	18	24	27	18	24	27
4	2	18.1	20.9	25.0	27.4	1	1	1	1.03	1.04	1.04	1.03	1.07	1.08	0.88	0.88	0.87
8	3	18.7	21.7	25.0	28.7	0.97	0.96	0.95	1	1	1	1	1.02	1.04	0.85	0.84	0.83
16	4	18.7	22.0	25.6	29.8	0.97	0.94	0.92	1	0.98	0.96	1	1	1	0.85	0.82	0.80
32	5	15.9	18.3	21.0	23.9	1.14	1.14	1.14	1.18	1.19	1.20	1.18	1.22	1.24	1	1	1
MEAN VALUE		18	21	24	27												

The determined factors for conversion of strength from samples with a given diameter to the strength which would have been achieved by testing concrete on other samples, for two strengths of concrete, are presented in Fig. 6 and 7.

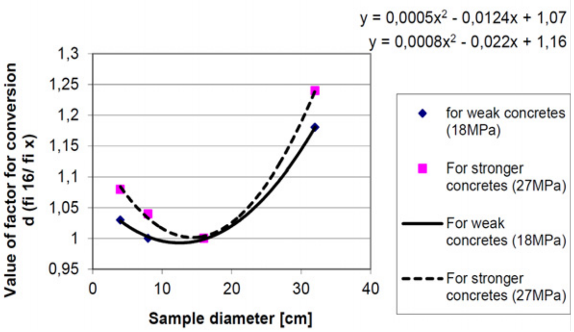

Fig. 6. Curve of factors for conversion of concrete strength from samples with various diameters to strengths which would have been achieved on samples with diameter Ø = h = 16 cm

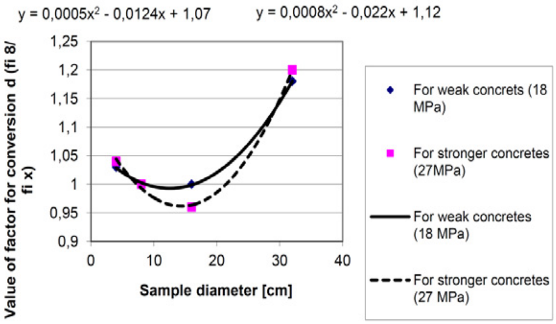

Fig. 7. Example of factors for conversion of concrete strength from samples with various diameters to strength which would have been achieved on samples with diameter Ø = h = 8 cm

4. Tests regarding strength of mortar in wall joints

It is known that the correlation dependency for concrete between the velocity of ultrasounds and compressive strength undergoes considerable changes, particularly because of the type of aggregate used and quantity of cement used. In the case of common, cement, cement and limestone construction mortars, the aggregate is quartz sand, and the quantity of binding material also does not change very considerably. In the study of Stawiski [23], results of tests were presented concerning dependency $f_c(C_R)$ for cement mortars with component proportions: cement to sand –1:8, 1:6, 1:3, cement-limestone: 1:1:7 and 1:2:10 and limestone 1:3. All results form a general entity without essential dispersions which can be described using one of the formulas given in Fig. 8.

For mortars up to 10 MPa, all curves are acceptable (parabola above its minimum). For strength above 10 MPa (C_R>1.7 km/s), this dependency is described better by the curve for cement mortars e.g. with formula $f_c = 1.292C_R^{3,9329}$.

Using the established dependencies, testing of mortar strength in the wall is already very simple, only approx. 2–3 cm of the surface layer of the mortar should be cut out because of carbonization of lime. Using heads with spot contact with the mortar, the velocity of the surface wave $C_R = l/t_n$ can be determined without any difficulties (where l – distance between spots of head application and t_n – net time of transmission of ultrasound impulse from transmitting to receiving head). Based on this, compressive strength of mortars is calculated from one of the formulas given in Fig. 8 for $f_c(C_R)$. The example of testing mortar in the wall is shown in Fig. 9.

For various regions of the world (various types of mortars), first one's own dependency $f_c(C_R)$ should be determined based on tests of standard samples (e.g. 4×4×16 cm) made in laboratory conditions using local aggregate (approximated to the aggregate in mortar in the wall) and strength range including strength of the mortar in the wall. The main benefit of this method is low variability of dependency $f_c(C_R)$ for mortars, thanks to which one can easily determine a dependency which can be used in various brick structures in the given region.

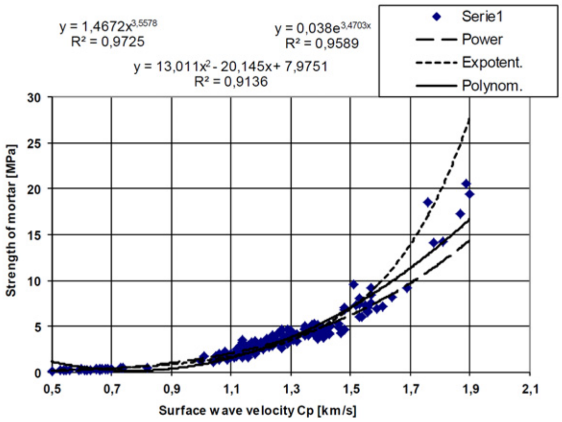

Fig. 8. Common correlation dependency $f_c(C_R)$ in the ultrasound surface method for all tested mortars

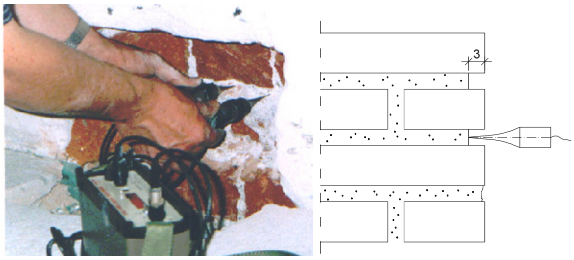

Fig. 9. Example of testing strength of mortar in the brick wall using ultrasound spot heads

5. Conclusions

The results obtained are interesting for several reasons. Generally, the correction of ultrasound velocity depending on route length is not used in practice. A mean value is calculated from the test results obtained and is the basis for calculation of strength. The results grouped by route length indicated that velocities determined on various routes considerably differ from each other. Converting them to a fixed measurement base enables elimination of the systematic error caused by the measurement technique.

It was expected that the regression curves would align in order from the smallest to the largest samples. In the coordinate system C_L – f_c, the curve for samples Ø16 cm is the highest, below there are Ø8 cm, Ø4 cm and Ø32 cm. Such a layout of the curves means that the commonly accepted principle stating that the smaller the sample, the higher the strength is not confirmed here. For this reason, conversion factors d from some samples to others achieve minimum in the range from Ø8 to Ø16, and then increase in both directions from this range. This is confirmed by test results by L'Hermite (Table 1).

Making use of the small influence of changes in sand to cement and limestone proportions on correlation dependency $f_c(C_R)$, such dependency, determined once in a given region, can be used to test the strength of mortars in existing brick walls after prior cutting of the carbonized surface layer of the mortar.

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