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

Stawiski Bohdan\textsuperscript{a}, Kania Tomasz\textsuperscript{b}*

\textsuperscript{a,b}Wroclaw University of Technology. Faculty of Civil Engineering, 50-370 Wroclaw, Poland

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.

*Corresponding author.
E-mail address: *Bohdan.Stawiski@pwr.wroc.pl; *kania.tomasz@vp.pl
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).

| 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 these forces? Let’s compare them using the sample Ø = h = 4 cm, with the bottom surface of 12.5 cm²:

- 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 – \( f_c = 15\text{–}37 \) MPa, samples Ø = h = 8 cm – \( f_c = 15\text{–}32 \) MPa, samples Ø = h = 16 cm – \( f_c = 15\text{–}36 \) MPa, samples Ø = h = 32 cm – \( f_c = 13\text{–}31 \) 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](image_url)

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:

\[ k = 1.2553x - 0.0478 \] (1)

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.
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:

for cylinders Ø 4 cm \[ f = 0.0233x^{5.1967} \] [MPa] (2)

for cylinders Ø 8 cm \[ f = 0.0201x^{5.3381} \] [MPa] (3)

for cylinders Ø 16 cm \[ f = 0.0118x^{5.7562} \] [MPa] (4)

for cylinders Ø 32 cm \[ f = 0.0228x^{5.1111} \] [MPa] (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] | Conversion factor d
|---------------------|-------------|--------------------------|---------------------|
|                     | Formula | For velocities \( C_L \) [km/s] | 04/ Øx = d | 08/ Øx = d | 016/ Øx = d | 032/ Øx = d |
|                     | Ø4 cm    | 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 |
|                     | Ø8 cm    | 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 |
|                     | Ø16 cm   | 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 |
|                     | Ø32 cm   | 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.
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 $f_c = 1.292C_R^{3.9229}$.

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.
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 $f_c(C_L)$, 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.

References

[1] PN-EN12504-1: 2011 Testing concrete in structures – Part 1: Cored specimens – Taking, examining and testing in compression. European Comittee for Standarization, 2011. 10 p. (in Polish).
[2] PN-EN12504-2: 2002 Testing concrete in structures – Part 2: Determination of rebound number. European Comittee for Standarization, 2002. 8 p. (in Polish).
[3] PN-EN12504-4: 2005 Testing concrete in structures – Part 4: Evaluating velocity of ultrasound wave. European Comittee for Standarization, 2005. 16 p. (in Polish).
[4] Indelicato, F., 1993. A statistical method for the assessment of concrete strength through microcores, Materials and Structures 26 (1993): 261-267.
[5] Ganguli, A., Rappaport, C., M., Abramo, D., Wadia-Fascetti, S., 2012. Synthetic aperture imaging for flaw detection in a concrete medium. NDT&E Int. 45(1): 79-90.

[6] Szilágyi, K., Borosnyói, A., Zsigovics, I., 2011. Rebound surface hardnness of concrete: Introduction of an empirical constitutive model. Construction and Building Materials, Volume 25, Issue 5: 2480-2487.

[7] Filonidow, A. M., Tretiakow, A. K., 1969. Kontrol betona ultrazvukom w gidrotekhnicheskom stroitelstve. Izdat, Energia, Moscow. (in Russian).

[8] Gudra, T., Stawiski, B., 2000. Non-destructive strength characterization of concrete using surface waves. NDT&E Int. 33(1): 1-6.

[9] Trtnik, G., Kavtic, F., Turk, G., 2009. Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. Ultrasonics, 49(2009): 53-60.

[10] Hassan, A. M. T., Jones, S. W., 2012. Non-destructive testing of ultra high performance fibre reinforced concrete (UHPFRC): A feasibility study for using ultrasonic and resonant frequency testing techniques. Construction and Building Materials, 35 (2012): 361–367.

[11] Aggelis, D. G., Hadjiyiangou, S., Chai, H. K., Momoki, S., Shiotani, T., 2011. Longitudinal waves for evaluation of large concrete blocks after repair. NDT&E Int. 44 (2011): 61-66.

[12] Madandoust, R., Bungey, J. H., Ghavidel, R., 2012. Prediction of the concrete compressive strength by means of core testing using GMDH-type neural network and ANFIS models. Computational Materials Science, 51 (2012): 261–272.

[13] Aliabdo, A. A. E., Mohamed A. E., 2012. Reliability of using nondestructive tests to estimate compressive strength of building stones and bricks. Alexandria Engineering Journal 51 (3): 193-203.

[14] Breysse, D., 2012. Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods. Construction and Building Materials, 33 (2012): 139–163.

[15] Kadir, K., Celik, A. O., Tuncan, M., Tuncan, A., 2012. “The Effect of Diameter and Length-to-Diameter Ratio on the Compressive Strength of Concrete Cores”. Proceedings of International Scientific Conference People, Buildings and Environment 2, pp. 219-229. ISSN: 1805-6784.

[16] Neville, A. M. 1995. Properties of Concrete. 5th Edition, Addison-Wesley Longman, U.K. 844 p.

[17] Bartlett, F. M., Macgregor, J. G., 1994. Effect of Core Diameter on Concrete Core Strengths, ACI Materials Journal 91(5, Sept.-Oct.): 460-470.

[18] Bartlett, F. M., Macgregor, J. G., 1993. Effect of Moisture Condition on Concrete Core Strengths, ACI Materials Journal 91(3, May-June): 227-236.

[19] Cramer, H., 1952. Die Abhängigkeit der Festigkeit von der Grosse der Versuchshorper betrachtet auf Grund der Wahrscheinlichkeitsrechnung. Österreichisches Ingenieur – Archiv 3 (in German).

[20] Kuczyński, W., 1959. O wytrzymałości betonu badanej na próbzkach różnych kształtów i wielkości (About strength of concrete tested on samples with various shapes and sizes), Archives of Civil Engineering, V(2): 61-80 (in Polish).

[21] Stawiski, B., 1976. Wpływ długości bazy pomiarowej i grubości kruszywa na wyniki badań jakości betonu metodą ultradźwiękową (The effect of measurement base length and aggregate thickness on results of concrete quality tests using the ultrasound method), in “Scientific Studies of the Civil Engineering Institute in the Wrocław University of Technology. ”Non-destructive tests in building industry”. Wrocław. pp. 69-76 (in Polish).

[22] Stawiski, B., 2000. “Badania wpływu długości drogi w betonie na rejestrowaną prędkość ultradźwięków” (Testing the influence of route length in concrete on registered ultrasound velocity, 29th National Conference Concerning Non-destructive Tests. Krynica: 143-148 (in Polish).

[23] Stawiski, B., 2008. Ultrasonic testing of concrete and mortar using point probes. Wrocław University of Technology. Publishing House of the Wrocław University of Technology. Wrocław. 154 p. (in Polish).