Models for Estimation of Concrete Compressive Strength Based on Experimental Research with Destructive and Non-destructive Methods

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Abstract This article presents experimental studies for assessing the concrete compressive strength in existing reinforced concrete members with destructive and non-destructive methods. For the destructive tests, 12 cube test specimens and 12 reinforced concrete beams (from which, 11 cores were drilled) were prepared in one day with the same recipe composition of the concrete. For two years, the reinforced concrete members were indoors, and in the following years, they were left outdoors exposed to external atmospheric influences. The research is aimed at the combined use (SonReb method) of two non-destructive methods: the method of elastic rebound (Schmidt rebound hammer) and ultrasonic pulse velocity method (UPVM) in order to achieve greater accuracy in assessing the compressive strength of concrete. Models have been developed describing the correlation between the determined compressive strength in the destructive test of cubes and cores with the measured rebound number and ultrasonic pulse velocity for the age of the concrete 1126th and 1926th day. The analysis was performed in Microsoft Excel environment.

Keywords Concrete · Compressive strength · Destructive · Non-destructive testing · SonReb

1 Introduction

One of the most important mechanical properties, which is important in design of reinforced concrete members and when determining their bearing capacity is the compressive strength of concrete [1]. The compressive strength changes over time and this requires monitoring during service. Methods for assessing the concrete compressive strength are destructive and non-destructive. The most reliable are the destructive methods, in which standard test specimens [2], prepared during the construction of the reinforced concrete members, or cores drilled from the existing reinforced concrete structures that are in operation are tested. Other methods are non-destructive testing

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(NDT) techniques and widely used in practice are the methods of elastic rebound, ultrasonic pulse velocity method (UPVM), ultrasonic pulse echo method, and others. Non-destructive tests are cheaper, less time-consuming, do not violate the integrity of the structure [3], but give an indirect assessment, which is why they are influenced by many factors, and their results can be unreliable. It is often appropriate to be used a combination of destructive methods with several NDT techniques. The theoretical principle of the combination of several NDT techniques is that sometimes the factors have the opposite effect on the measurement results of the different methods. Combining the ultrasonic method with the method of elastic rebound is the most popular combination and is known as SonReb [4, 5].

This paper examines the effectiveness of the combination of destructive and non-destructive techniques (rebound number determined with Schmidt hammer and ultrasonic velocity with UPVM).

2 Methods Used in Experimental Research

The following four methods were used in the experimental studies:

Method of elastic rebound (Schmidt Hammer) determines the surface hardness of concrete, and hence, the probabilistic compressive strength of concrete in new and existing reinforced concrete structures [2, 6–9]. The Schmidt hammer measures the magnitude of the elastic rebound of a spring-loaded steel body from a concrete surface. The measured rebound number is related to the surface toughness of the concrete. The test is sensitive and the results can be affected by the type of cement, the type of aggregate, curing and age of the concrete, surface condition, and moisture content of concrete surface, the carbonization of the concrete, and others.

Non-destructive ultrasonic pulse velocity method (UPVM) uses the propagation of ultrasonic waves introduced into concrete, where they propagate, dissipate, and are reflected from the boundary between two environments [8–12]. The measuring instruments consist of an ultrasonic oscillation generator, transmitter, receiver, amplifier, and reading device. The generator generates high-frequency signals with a frequency of 25–150 kHz. The transmitter is a piezoelectric crystal. The receiving piezoelectric transducer registers ultrasonic waves and converts them into electrical signals. From the ultrasonic signal velocity, probabilistic compressive strength can be determined.

SonReb Method makes it possible to apply the combination of the measurement re-sults with UPVM and the Method of elastic rebound [2, 13] with the obtained compres-sive strength in a destructive test of standard test specimens (prepared from the same concrete mix on the day of construction of the reinforced concrete members) or cores drilled from a reinforced concrete structure that is in operation. To assess the compressive strength, a correlation is sought between the independent variables (velocity of the ultrasonic signal and the magnitude of the rebound) and the dependent variable–compressive strength of the concrete [9, 14]. In the literature, many authors have reported empirical correlation formulas for relationship of concrete compressive strength f_c with non-destructive measurements of the rebound number and the ultrasonic velocity. The models obtained from them are linear, power, exponential, polynomial, or others. In cases where there is no data on the concrete used, an equation of the type is used [2, 3, 17]:

$$f_{c,\mathrm{SonReb}} = aR^b V^c, \tag{1}$$

where *a*, *b*, *c* are constants; *V*—ultrasonic pulse velocity; *R*—rebound number.

The coefficients *a*, *b*, and *c* in Eq. (1), and correlation curves between compressive strength and non-destructive test results can be obtained from the Excel regression analysis function [15]. The relationship between the compressive strength and NDT measurements is called "conversion model." The resulting iso-strength curves can give a correct prediction of the compressive strength of concrete and are adapted only to the specific case (specific reinforced concrete structure) for which they are derived [1].

Destructive methods are the most reliable way to assess the mechanical properties of concrete; although, they are significantly invasive [2]. They are applied on standard test specimens or on cores taken from reinforced concrete structures. The test specimens are tested for compression till failure on testing machines for materials. The load speed is constant. The load is applied to the test specimen without hit and increases evenly until failure; the force *F* is reported; the compressive strength f_c is calculated.

In this paper, the author aims to develop correlation equations and curves for determining the compressive strength of concrete in existing reinforced concrete beams, using destructive and non-destructive methods. Non-destructive and destructive testing are in accordance with European standards.

3 Experimental Setup

The specimens for determining the compressive strength of the concrete f_c on the 1126th and 1926th day of laying the concrete mix were prepared in one day of concrete with the same recipe composition (Fig. 1).

Part of the research was done on four series of reinforced concrete beams. The series differ in provided longitudinal reinforcement, concrete cover, and reinforcement ratio. Their structural parameters were selected so as to correspond to the characteristic parameters of the beams designed in practice in industrial and civil construction. They were prepared of concrete class C25/30, fine fraction of coarse aggregate ($d_{\max} = 12$ mm), and consistency S3. The reinforced concrete members were indoors for two years, and in the following years, they were left outdoors, exposed to external atmospheric influences.

For experimental study of the concrete strength, characteristics were prepared 12 cubes with dimensions 150/150/150 mm in the same day with the reinforced concrete beams. The cubes were tested at age 1126th day. They were made from the same

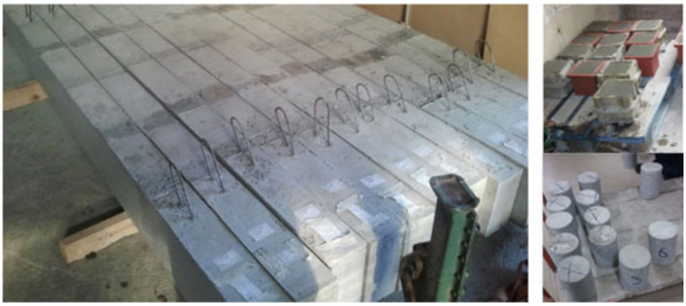

Fig. 1 Experimental specimens for non-destructive and destructive testing (personal archive)

recipe composition of concrete as for reinforced concrete beams. Their dimensions were chosen depending on the size of the coarse aggregate—EN 12390-1:2012. The specimens were prepared according to EN 12390-2:2009, and the sampling of the concrete mix was done according to EN 12350-1:2009.

To study the concrete compressive strength at age 1926th day, 11 cores with a diameter (D) Ø100 mm were taken from the beams at a depth ranging from 151 to 156 mm from places without visible cracks, pores, cavities, defects, and reinforcement on the surface of the beams [2, 16, 17]**.** The measurements were done with an accuracy of 1 mm. The choice of core diameter is regulated by the D/A ratio, where A is the maximum size of the coarse aggregate. According to EN 12504-1:2019, this ratio must be equal to or greater than 3, 0. The drilling of cores is in accordance with EN 12504-1:2019. In real conditions, the hole obtained when drilling the core is filled with concrete or other suitable fillers [1]. Before performing the tests, the selected 11 concrete test specimens (cores) were prepared by cutting off their ends on both sides, and they become cylinders with a depth of 100 mm and a diameter of 100 mm, i.e., the l/d ratio is equal to 1.

4 Tests and Results

For determining the compressive strength of concrete through its surface, hardness was determined the rebound number (Fig. 2a), according to EN 12504-2:2012 and a Digi Schmidt hammer was used. On the age of concrete 1126th day on each cube on two opposite sides, 10 hits were made. The distances between the centers of hits and from the edges of the cubes were not less than 30 mm. In each series of tests, the direction is horizontal. The rebound number varies in the range $R = 44–49.5$.

When testing the beams at age 1926th day on the two opposite sides in places where the cores will be drilled, 10 measurements were made by the method of elastic rebound. In each series of tests, the direction is vertical from top to bottom. Each mark on the surface was checked after the rebound, and if the hit had fallen on a surface pore, the result was not taken into account. The median value of the rebound

(a) (b) (c)

Fig. 2 Determining the rebound number (**a**); ultrasonic signal velocity (**b**); compressive strength by destructive tests of specimens (**c**) (personal archive)

number *R* of the 10 hits for each test point was calculated. The rebound number varies in the range $R = 45–52$, i.e., the rebound number increases with age.

A portable Proceq TICO ultrasonic device was used for the experimental determination of the ultrasonic signal velocity (Fig. 2b). The operating frequency of the transmitter and receiver is 54 kHz, and the resolution is 0.1 µs. The surfaces of 12 cubic test specimens and the reinforced concrete beams are smooth. Ensuring good contact between the piezoelectric transducers and the concrete surfaces is done by a special coupling paste. For each test specimen, 10 measurements of the ultrasonic velocity were made according to EN 12504-4:2005. The transmitter and receiver of the ultrasonic device were located symmetrically against each other. Before each measurement, the equipment was calibrated with a reference cylindrical body with a known velocity.

Ultrasonic velocity measurements on age 1126th day were made on two opposite sides of the cubes, and measurements on age 1926th day were made on two opposite sides of the beams in places from which the cores would be taken. The value of UPV for age 1126th day is $V = 4.335–4.442$ km/s, and for the 1926th day, it is $V = 4.578–4.876$ km/s, i.e., the velocity of the ultrasonic signal increases with age.

The compressive strength of concrete from a test of 12 cubes with standard dimensions at age 1126th day was determined with destructive tests (Fig. 2c) according to EN 12390-3:2009. The test specimens were tested on compression till failure on a calibrated material testing machine type: 50-C4652 (0–2000) kN, CONTROLS Automax 5, corresponding to EN 12390-4:2001. A constant load rate of 0.5 MPa/s has been selected, according to the requirements of the EN 12390-3:2009 standard. The load is applied to the test specimen without hit and increases evenly until failure, the force F [kN] was recorded and compressive strength [N/mm^2] was calculated.

At age of concrete 1926th day, the drilled cores were tested on the same machine, and the compressive strength was determined by dividing the load at failure by the cross-sectional area of the core. The cores were taken from the members according to EN 12504–1:2019, and the compressive strength was determined according to EN

12390-3:2009. According to BDS EN 13791:2007/NA:2011, if the ratio of the height of the core L to the diameter D is equal to 1, the obtained compressive strength must be equal to the compressive strength of a cube with a side of 150 mm. Before testing the cores, their mass and geometric dimensions were determined. The compressive strength f_c for age 1126th day varies from 39.97 to 47.12 MPa and for the 1926th day varies from 42.4 to 52.5 MPa, i.e., it increases with age.

5 Analysis of Results. Models and Correlation Curves

Drawing of regression (correlation) curves from mathematical models for the dependences of the compressive strength of concrete obtained by the destructive method on the rebound number, on the ultrasonic velocity and on $f_{c,\mathrm{SonReb}}$ determined with the SonReb method were made with Excel. The obtained graphs show the approximating line, the equations of this line, and the value of the correlation coefficient R^2, by which the reliability of the approximation can be estimated. The closer its value is to 1, the more precisely the selected function approximates the data. For obtaining correlation curves between the results of concrete compressive strength obtained by destructive method, and the results of non-destructive tests the constants a, b, and c were determined in Eq. (1), using regression analysis in Microsoft Excel and $f_{c,\mathrm{SonReb}}$ was determined.

When creating empirical correlation formulas to study the effectiveness of the combination of non-destructive measurements with the destructive testing of test specimens, the coefficient R^2 was compared with the models obtained from those with non-destructive techniques separately.

Figures 3 and 4 show the dependences of the compressive strength of concrete, determined by a destructive test of cubes at age 1126 days and destructive test of cores at age 1926 days on the rebound number R and on the velocity of the ultrasonic

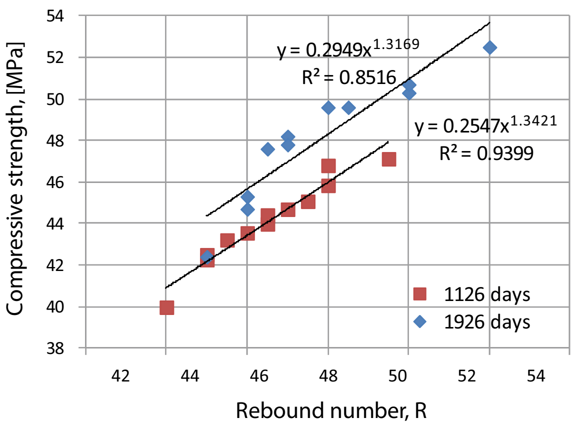

Fig. 3 Relationship of the concrete compressive strength, determined by destructive tests of specimens on the rebound number R at the age of 1126 and 1926 days

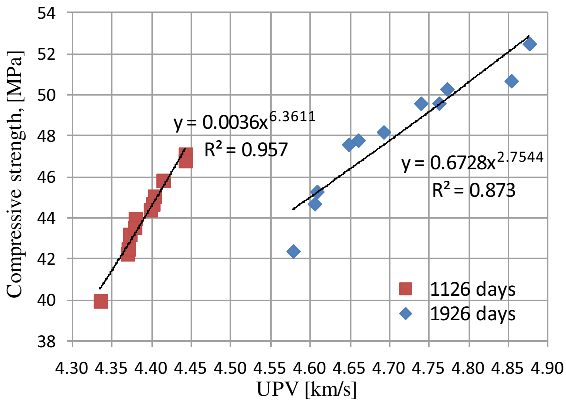

Fig. 4 Relationship of the concrete compressive strength, determined by destructive tests of specimens on the UPV at the age of 1126 and 1926 days

signal (UPV). The dependencies show that the magnitude of the rebound number and the UPV increases with increasing compressive strength, and the accuracy of the selected power equations have a very good correlation—the parameter R^2 is 0.940 and 0.957, respectively, at age of concrete 1126 days and the parameter R^2 is 0.852 and 0.873, respectively, at age of concrete 1926 days.

Figure 5 shows the dependence of the compressive strength determined by of the destructive test of cubes at age 1126 days and destructive test of cores at age 1926 days on the compressive strength determined by the SonReb method according to formula (1). The parameter R^2_{combined} in the combined use of Schmidt hammer and UPVM for age 1126 days is equal to 0.9728, for age 1926 days is equal to 0.8824 (it is fulfilled that $R^2_{\text{combined}} > R^2_{\text{single}}$), i.e., the combination gives a more reliable estimate compared to the use of the two techniques separately.

For the specific experimental data on the compressive strength of concrete, determined by destructive testing of test specimens, on the magnitude of the rebound number R and on UPV at the age of 1126 days, Eq. (1) takes the form:

$$f_{c,\text{SonReb}} = 0.0171 R^{0.5593} V^{3.8562} \tag{2}$$

Based on Eq. (2) with Excel, multiple regression curves were obtained to determine the compressive strength of concrete for the specific reinforced concrete structure (Fig. 6) [1, 15]. The resulting expression for $f_{c,\text{SonReb}}$ can be used to determine the compressive strength for any region of the existing reinforced concrete structure.

For the specific experimental data on the compressive strength of concrete, determined by destructive testing of test specimens, on the magnitude of the rebound number R and on UPV at the age of 1926 days, Eq. (1) takes the form:

$$f_{c,\text{SonReb}} = 0.5003 R^{0.39} V^{1.9723} \tag{3}$$

Based on Eq. (3), multiple regression curves were obtained to determine the compressive strength for the specific reinforced concrete structure (Fig. 7) [1, 15].

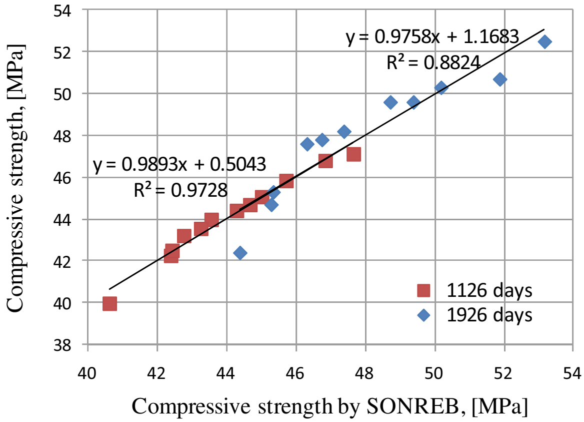

Fig. 5 Relationship of the compressive strength, determined by destructive tests of specimens on the compressive strength determined by SonReb at the age of 1126 and 1926 days

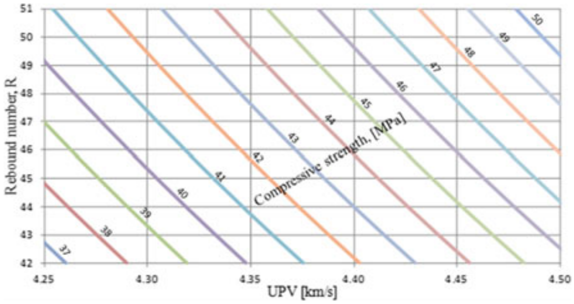

Fig. 6 Iso-strength curves for determining the compressive strength of concrete obtained by the SonReb method at the age of 1126 days

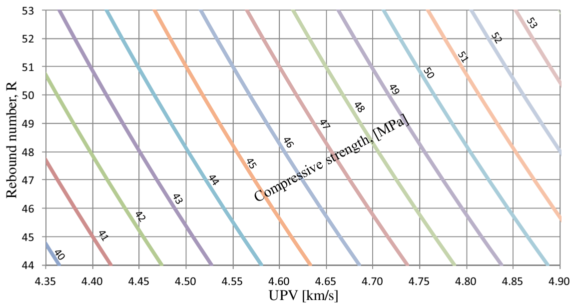

Fig. 7 Iso-strength curves for determining the compressive strength of concrete obtained by the SonReb method at the age of 1926 days

6 Conclusion

Based on the experimental studies and the developed models, the following conclusions can be made:

- The correlation coefficient R^2 of the proposed models for the dependence of the compressive strength of concrete f_c, determined by the destructive testing of

specimens on the rebound number R varies from 0.852 to 0.94. The coefficient R^2 of the proposed models for the dependence of the compressive strength of concrete f_c, determined by the destructive testing of specimens on UPV varies from 0.873 to 0.957. This shows a good relationship between compressive strength, rebound number value, and UPV. Thus, rebound number and UPV are important predictors;
- Dependence on only one test method (rebound hammer test or ultrasonic pulse velocity test) does not always give sufficiently accurate results. In the developed correlation curves between the compressive strength of concrete f_c, determined by the destructive testing of specimens and the compressive strength determined by the method SonReb $f_{c,\text{SonReb}}$, the correlation coefficient R^2 varies from 0.8824 to 0.9728. This shows the best relationship and greater accuracy between compressive strength and the combination of two non-destructive methods. The development of such dependencies helps for more accurate assess and track the characteristics of concrete over a long period of time;
- If for a reinforced concrete structure, we have results for compressive strength of concrete f_c, obtained from destructive testing of specimens, value of rebound number and velocity of the ultrasonic pulse. For a given number of test points, the value of compressive strength $f_{c,\text{SonReb}}$ can be determined using correlation curves for any part of the structure. This allows to reduce the number of destructive tests of cores taken from existing reinforced concrete structures and to limit damage, using only the values of the rebound number and UPV for the whole structure.

From the experiments performed and the derived models for determining the compressive strength of concrete with the SonReb method, there is still no general consensus in the literature on the effectiveness of this combination, and this approach needs further research.

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References

1. Alwash M (2017) Assessment of concrete strength in existing structures using nondestructive tests and cores: analysis of current methodology and recommendations for more reliable assessment. Mechanics. Université de Bordeaux. NNT:2017BORD0587
2. Minutolo V et al (2019) The use of destructive and non-destructive testing in concrete strength assessment for a school building. IJARET 10(6):252–267. https://doi.org/10.34218/IJARET.10.6.2019.028
3. Jain A et al (2013) Combined use of non-destructive tests for assessment of strength of concrete in structure. Pr Eng 54:241–251. https://doi.org/10.1016/j.proeng.2013.03.022
4. Cristofaro M et al (2012) Mechanical characterization of concrete from existing buildings with SonReb method. 15 WCEE, Lisboa
5. Hannachi S, Guetteche M (2012) Application of the combined method for evaluating the compressive strength of concrete on site. Open J Civ Eng 2. https://doi.org/10.4236/ojce.2012.21003

6. Wang X, Jiang K (2016) Quality control and evaluation methods of concrete engineering and its reliability analysis. Int J Simul Syst Sci Technol 17. https://doi.org/10.5013/IJSSST.a.17.17.15
7. Nobile L, Bonagura M (2013) Accuracy of non-destructive evaluation of concrete compression strength. In: 12th ICSSNDT, Slovenia, pp 57–64
8. Zatar W (2014) Assessing the service life of corrosion-deteriorated reinforced concrete member highway bridges in West Virginia. Marshall University
9. Khan A (2002) Guidebook on non-destructive testing of concrete structures. IAEA, Training Course Series 17, Vienna
10. Karaiskos G et al (2015) Monitoring of concrete structures using the ultrasonic pulse velocity method. Smart Mat Struct 24 (11). https://doi.org/10.1088/0964-1726/24/11/113001
11. Lorenzi A at al (2007) Ultrasonic pulse velocity analysis in concrete specimens. IV Conf Panamericana de Ensayos No Destructivos, Buenos Aires
12. Naik T et al (2004) The ultrasonic pulse velocity method. Handbook on nondestructive testing of concrete. CRC Press, USA
13. Pucinotti R (2007) The use of multiple combined non destructive testing in the concrete strenght assessent: applications on laboratory specimens. 4th ICNDT, Crete, Greece
14. Chandak N, Kumavat H (2020) SonReb method for evaluation of compressive strength of concrete. In: IOP IOP conference series: materials science and engineering (MSE), vol 810, issue no 1. https://doi.org/10.1088/1757-899X/810/1/012071
15. Nikhil M et al (2015) The use of combined non destructive testing in the concrete strength assessment from laboratory specimens and existing buildings. Int J Curr Eng Sci Res (IJCESR) 2(5):55–59
16. Jedidi M (2018) Evaluation of the concrete quality using destructive and non-destructive tests. MOJ Civil Eng 4(4):219–223. https://doi.org/10.15406/mojce.2018.04.00095
17. Dauji S et al (2019) Conservative characteristic strength of concrete from nondestructive and partially destructive testing. J Asian Concr Fed 5(1):25–39. https://doi.org/10.18702/acf.2019.06.30.25