Further Investigations Regarding a New Approach on Estimating Concrete Compressive Strength via Ultrasonic Pulse Velocity

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Abstract. One main focus pursued by many researchers is developing faster and cheaper non-destructive methods (NDT), whilst increasing the accuracy in estimating the concrete mechanical properties, mainly the compressive strength. In many cases, the NDT approach is preferred because of its non-destructive nature. Despite the fact that the destructive testing (DT) delivers more accurate results, the number of concrete cores is, in general, limited because of invasive nature upon evaluated elements and thus can lack sufficient data for the analyze and further on, for drawing appropriate conclusions. Furthermore, it is a known fact that concrete strength may vary between the same elements. With the DT it is difficult to quantify the internal flaws of the concrete, such as internal cracks, delamination, or voids, because it is recommended to avoid those areas when coring. The purpose of this paper is to further investigate a proposed method on a new set of concrete cores extracted from a multistorey building, in order verify its validity and accuracy. The new approach is solely based on ultrasonic pulse velocity (UPV) testing which delivers data concerning relevant parameters (air-dry density, dynamic modulus of elasticity, static modulus of elasticity) leading to concrete compressive strength evaluation. In the process of determining the dynamic modulus of elasticity, the dynamic Poisson's coefficient was considered in accordance with values provided by the technical literature, and it is not experimentally determined for this step of the investigation.

Keywords: Non-destructive · Ultrasonic Pulse Velocity · Modulus of elasticity

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1 Introduction

Reinforced concrete (RC) structures are crucial components of the construction industry, and assessing and ensuring their quality control has become increasingly important. The primary focus of quality control is determining the mechanical properties of concrete, including density, compressive strength, and modulus of elasticity. While these properties can be determined in the laboratory on concrete samples, in case of new buildings, the non-destructive testing (NDT) is a more feasible and suitable solution for the existing ones.

Due to their non-destructive nature, NDT methods require fewer resources and provide faster results than destructive testing (DT) [1]. One popular NDT approach is ultrasonic pulse velocity (UPV) [2], which can be used to detect internal flaws, such as cracks, delamination, or deteriorations due to environmental factors, such as chemical aggressivity or freezing [3]. UPV can also be used to estimate concrete compressive strength. Researchers have attempted to establish a direct relationship between NDT and concrete compressive strength, using a single variable, such as UPV, or multiple variables, such as UPV and rebound hammer Schmidt (RHS) [4–7]. However, none of the equations developed could be considered valid for all types of concrete.

Facaoaru [8] developed the SONREB method, which uses a combination of UPV and RHS to estimate concrete compressive strength. Although this method delivers results with high accuracy, it relies on concrete information, namely the type and dosage of cement, as well as the nature and granulometry of the aggregates. These factors are often unknown in the case of old buildings, and assuming incorrect coefficients can lead to significant errors, ranging from 25% up to even 30% [9]. Samarin and Smorchevsky [10] proposed a modified SONREB method that only involves the aggregate type and concrete's age as variables.

The RILEM NDT4 [11] developed the ISO-based resistance curves, which enable the estimation of concrete compressive strength using RHS and UPV values through interpolation. Over time, many formulations were developed based on experimental data obtained by testing concrete samples extracted from existing buildings [12–18].

This paper aims to further validate a proposed method for estimating concrete compressive strength using UPV to determine the air-dry density, dynamic and static moduli of elasticity, and ultimately concrete compressive strength. The proposed method was developed during previous research, and it generally aims to provide more accurate and reliable results in the field of NDT testing approaches.

2 Materials and Methods

2.1 Destructive Method (DT)

The method presumes the coring of cylindrical concrete samples from an existing structure. These samples are used to determine the compressive bearing capacity (f_{car}) in laboratory, after specific processing. The values obtained do not represent the values equivalent to cubic or cylindrical strength. In order to obtain the equivalent concrete compressive strength (f_{is}), the compressive bearing capacity must be amended with several correctional factors which depends on factors like: diameter, moisture, samples processing, etc. Romanian Norm NP 137 [9] provides the equation for determining the equivalent concrete compressive strength:

$$f_{is} = a \cdot b \cdot c \cdot e \cdot g \cdot d \cdot f_{car} \quad (1)$$

where:

f_{is} – equivalent concrete compressive strength [MPa];
a – coefficient that considers the influence of the core diameter [-];
b – coefficient that considers the height/diameter ratio [-];
c – coefficient that considers the influence of the degraded layer [-];
e – coefficient that considers the nature of the leveling layer [-];
g – coefficient that considers the humidity of the concrete core [-];
d – coefficient that considers the position and diameter of the reinforcement bars [-];
f_{car} – resulted compressive bearing capacity [MPa];

Despite the fact that the destructive method delivers highly accurate results, it consumes more resources and it also has limitation in terms of core number due to sever-al reasons: the destructive nature of the testing can affect the evaluated structural element, drastically reducing the sampling number, the coring conditions might be quite a challenge, due to low accessibility on site, technological and design conditions which can even forbid the coring certain, designated elements of a structure. In this study, DT was used as control method, for the validation of the proposed NDT methodology.

2.2 Ultrasonic Pulse Velocity (UPV)

Ultrasonic Pulse Velocity (UPV) is a non-destructive testing (NDT) method used to evaluate the integrity and quality of concrete structures by the means of recording the velocity of ultrasonic pulses through concrete; consequently, it provides information about the density and elasticity of the material.

The ultrasonic pulse velocity is one of the most used NDT of concrete, due to its many advantages:

- It can be applied to all types of elements;
- It can be used regardless of the thickness of the element;
- It can be applied also on elements with reduced accessibility, on only one face/surface;
- The testing is done in a short amount of time;
- It can be used to localize internal defects such as voids, delamination's, etc.

UPV testing works by sending an ultrasonic pulse through the concrete mass and measuring the time it takes for the pulse to travel through the material and return to the origin. The velocity of the pulse can be calculated based on the distance traveled by the wave and the recorded time. The velocity of the pulse is related to the elastic properties of the concrete, which can be used to infer the quality of the material.

The testing procedure involves the careful preparing the surface of the concrete by cleaning and polishing it and attaching the ultrasonic pulse generator and receiver to opposite sides of the material. The generator is then triggered to send a pulse through the concrete mass, and the time consumed for the pulse to return to the receiver is measured, determining the pulse velocity as distance to time ratio. The procedure is typically repeated multiple times, at different locations on the concrete element, in order to obtain the representative sampling of the material.

As previously mentioned, the velocity of the ultrasonic pulse through concrete can be used to evaluate the material quality. Generally, a higher velocity indicates a denser and more elastic material, while a lower velocity indicates a lower density and less elastic material. The results of UPV testing can be used to identify areas of weakness or damage in concrete structures and also to evaluate the quality of newly placed concrete.

2.3 Dynamic Modulus of Elasticity

Dynamic modulus of elasticity is calculated based on the response of concrete when subjected to cyclic loading. It is related to the static modulus of elasticity (E_s) by the ratio of the dynamic modulus to the static modulus, also known as the damping ratio (ξ). Generally, the dynamic modulus is lower than the static modulus due to the presence of viscoelastic behavior in concrete, which results in energy dissipation and a reduction in stiffness [19].

Dynamic modulus of elasticity can be determined using Ultrasonic Pulse Velocity (UPV) by applying the Eq. 2 provided by Romanian Norm GE 039 [19].

$$E_d = \frac{(1+\Theta_d)\cdot(1-2\cdot\Theta_d)}{1-\Theta_d}\cdot\frac{\gamma}{g}\cdot V_L^2 \tag{2}$$

where:

E_d—dynamic modulus of elasticity [MPa];

Θ_d—dynamic Poisson's ratio [-];

γ—air dry density [kg/m^3];

g—gravitational acceleration [m/s^2];

V_L—ultrasonic pulse velocity [km/s];

In this study the dynamic Poisson's ratio was assumed the value $\Theta_d = 0.25$, which is a normal value accepted for concrete preserved in the air. Therefore Eq. 2 transforms into Eq. 3:

$$E_d = 0.83\cdot\frac{\gamma}{g}\cdot V_L^2 \tag{3}$$

In terms of air-dry density, the study conducted by Salman [20] presents a linear correlation between air-dry density (γ) and UPV in the form of Eq. 4:

$$\gamma = 114.8\cdot V_L + 1813 \tag{4}$$

where:

γ—air-dry density [kg/m^3];

V_L—ultrasonic pulse velocity [km/s];

Consequently, the dynamic modulus of elasticity can be determined by the means of only UPV measurements.

2.4 Static Modulus of Elasticity

The static modulus of elasticity is a measure of the stiffness of a material, therefore representing an important property of concrete It is calculated as the stress to strain ratio when specimen is subjected to a static loading, and it can be used to material behavior under various loading conditions.

The static modulus of elasticity of concrete can be determined by conducting a static compression test on a cylindrical or cubic specimen. The specimen is loaded until it reaches its maximum strength, and the stress-strain relationship is recorded and the slope at first loading and after three loading cycles. The static modulus of elasticity is then calculated as the slope of the linear portion of the stress-strain curve [21].

The static modulus of elasticity of concrete is dependent on several factors, including the type and proportions of the constituent materials, the curing conditions, and the age of the material. Therefore, it is important to carefully control these variables during testing to obtain accurate and reliable results. The determination of the static modulus of elasticity of concrete is crucial to ensure the safety and reliability of concrete structures, and therefore, it is important to follow the appropriate testing procedures and standards.

In engineering design and analysis, the static modulus of elasticity is used to estimate the deformation of concrete under load. This information is important for determining the load-carrying capacity of concrete structures, and also for evaluating the cracking pattern and other forms of damage. The static modulus of elasticity is also used to calculate deflections and strains in concrete beams and slabs, which are important considerations in the design of structures to ensure their stability and safety.

The static modulus of elasticity can be determined with Eq. 5 presented by Noguchi et al. [22], but it also depends on concrete compressive strength (f_{is}).

$$E_s = 2.1 \cdot 10^5 \cdot (\frac{\gamma}{2.3})^{1.5} \cdot (f_c/200)^{1/2} \tag{5}$$

where:

E_s—static modulus of elasticity [MPa];

$f_c = f_{is}$—concrete compressive strength [MPa];

γ—concrete air-dry density determined via UPV [kg/m^3].

In this study the dynamic modulus of elasticity was determined via UPV and the static modulus of elasticity was determined separately, by using Eq. 5, using the concrete compressive strength, available from the destructive testing performed on concrete cores. With the two moduli of elasticity known, a linear correlation was established between them in the form of Eq. 6.

$$E_s = 0.88 \cdot E_d \tag{6}$$

With the static modulus of elasticity determined via Eq. 6, in Eq. 5 the only unknown variable is the concrete compressive strength (fc). Extracting that parameter and rearranging the equation, it becomes a relationship where concrete compressive strength depends on variables determined via UPV.

$$f_c = (E_s^2 \cdot 200)/[2.1 \cdot 10^5 \cdot (\gamma/2.3)^{1.5}]^2 \tag{7}$$

2.5 Experimental Procedure

A flowchart of the proposed method is presented in Fig. 1 for a better understanding.

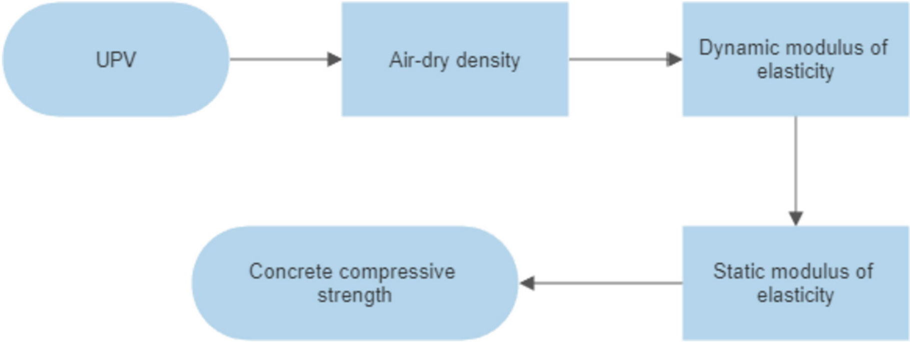

Fig. 1. Flowchart of the proposed approach.

The study involved 22 concrete cores (Fig. 2), 94 mm in diameter, extracted from various areas of different slabs of the same building. The cores were processed according to the Romanian Norm NP 137 [9]. The specimens were cut at both ends using a wet diamond disk and then conditioned at T: (21 ± 3) °C and RH: (50 ± 5) % for 5 days until testing. The cores were cured for 5 days prior to UPV testing in order to dry out the humidity absorbed during the wet cutting, which can affect the UPV results. Figure 2 shows the concrete sample after cutting and conditioning, and before UPV testing and further destructive, compressive testing (DT).

Fig. 2. Concrete core specimens.

The non-destructive testing, namely UPV, was conducted with a Tico Proceq device equipped with 54 kHz transducers (Fig. 3) and the destructive testing was performed with respect to SR EN 12390-3 [23], by the means of a 300 kN hydraulic, compressive testing machine at a loading rate of 0.6 MPa/s.

Fig. 3. UPV testing.

3 Results and Discussions

3.1 Proposed Method vs. Destructive Method

In order to verify the effectiveness of the proposed method it is recommended to use a statistical approach. In this particular case, the accuracy (Ac) and the root mean square error (RMSE) were chosen as statistical tools to measure the performance of the method. Accuracy can be defined as the degree to which a measurement, calculation, or prediction represents the true or correct value of a quantity or parameter [24]. The RMSE is a commonly used metric for measuring the accuracy of predictions and represents the average difference between the predicted values and the actual (measured) values.

Table 1 presents the concrete compressive strength data obtained from both the traditional destructive method and the proposed method. Additionally, the accuracy of the proposed method is reported in the table. The accuracy is an indicator of how closely the values obtained from the proposed method align with the true values obtained from the traditional method. A higher accuracy value indicates better agreement between the two methods, while a lower accuracy value indicates greater divergence between the results obtained from the two methods.

When considering the compressive strength of the concrete, the measured values range from a minimum of 34.0 MPa to a maximum of 48.5 MPa, with a mean value of

Table 1. Measured and predicted compressive strength.

Core no.	Measured compressive strength [MPa]	Predicted compressive strength [MPa]	Accuracy [%]
1	48.5	45.1	93
2	37.5	40.5	93
3	44.5	45.0	99
4	45.5	46.0	99
5	48.0	44.7	93
6	39.5	39.5	100
7	37.5	38.9	96
8	34.0	39.8	85
9	41.5	45.1	92
10	44.0	38.2	87
11	39.5	40.6	97
12	40.0	36.6	92
13	34.5	35.4	98
14	38.0	41.4	92
15	47.0	41.7	89
16	43.5	36.7	84
17	41.5	40.0	97
18	43.0	48.8	88
19	39.5	39.8	99
20	43.0	39.8	93
21	34.5	37.3	92
22	38.5	42.4	91

41.0 MPa. In terms of the proposed method, the accuracy of the predicted values ranges from 84% to 100%, with a mean accuracy value of 93%.

However, upon closer inspection of the results, it can be observed that the predicted values tend to be overestimated in more than half of the cases. This suggests that the proposed method may be prone to overestimating the compressive strength of the concrete, particularly when compared to the reference values, obtained from the traditional, destructive method. It may be necessary to investigate the underlying causes of this overestimation and adjust the proposed method accordingly, to improve its accuracy.

The RMSE value for the predicted values was found to be 4.75. This suggests that the model had an average error of 4.75 units in its predictions compared to the actual measured values. The RMSE value is relatively low compared to the range of the actual values and the variability in the data.

In Fig. 4 a graphical representation of the two sets of values is presented for a better understanding.

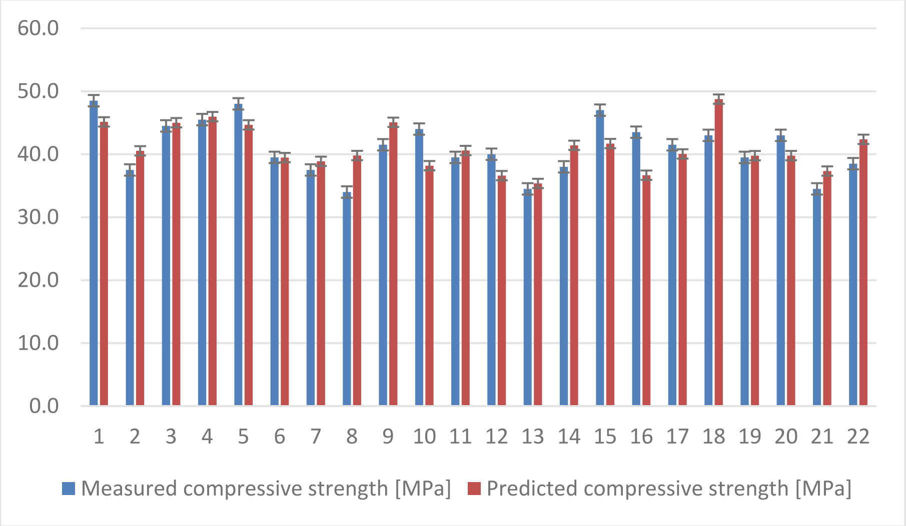

Fig. 4. Measured vs. predicted values.

4 Conclusions

The objective of this study is to evaluate the outcomes of integrating on-site ultrasonic pulse velocity (UPV) measurements with theoretical evaluations using a combination of equations established by various researchers. These equations enable the association of ultrasonic pulse velocity values with the dynamic modulus of elasticity, the static modulus of elasticity, and ultimately, concrete compressive strength.

It is crucial to ensure a thorough surface preparation to eliminate any potential errors that may arise during the on-site UPV testing. Moreover, when compared to prior research [25], it is evident that a calibration between the dynamic and static modulus of elasticity is necessary since the linear equation is not universally applicable to all types of concrete and this is a direction on which future research will be directed on.

The results of this study indicate that the predictive model had a moderate level of accuracy in its predictions for compressive strength. Future research needs to focus on improving the accuracy of the model and reduce the level of error in its predictions.

Further investigation is required to determine the factors that influence the dynamic relationship between the two moduli of elasticity. It is essential to experimentally determine the static modulus of elasticity in laboratory on different concrete mixtures. The concrete mixtures must have various compositions, additives, aggregate sizes, and variations in the water-cement ratio, in order to identify a relationship between the two moduli of elasticity that includes dependent variable. This is an important step in refining the proposed method and improving its accuracy.

References

1. Karahan, Ş, Büyüksaraç, A., Işık, E.: The relationship between concrete strengths obtained by destructive and non-destructive methods. Iran. J. Sci. Technol. Trans. Civ. Eng. **44**, 91–105 (2020)
2. Cristofaro, M.T., Viti, S., Tanganelli, M.: New predictive models to evaluate concrete compressive strength using the SonReb method. J. Build. Eng. **27**, 100962 (2020)
3. Malhotra, V.M., Carino, N.J.: Handbook on Nondestructive Testing of Concrete. CRC Press, Boca Raton (2003)
4. Masi, A.: La stima della resistenza del calcestruzzo in situ mediante prove distruttive e non distruttive. Il Giornale delle Prove non Distruttive Monitoraggio Diagnostica, vol. 1 (2005)
5. Cristofaro, M.T., D'Ambrisi, A., De Stefano, M.: Nuovi modelli previsionali per la stima della resistenza a compressione del calcestruzzo con il metodo Sonreb (2009)
6. Faella, G., Guadagnuolo, M., Donadio, A., Ferri, L.: Calibrazione sperimentale del metodo SonReb per costruzioni della Provincia di Caserta degli anni'60'80. In: Proceedings of 14th Anidis Conference, Bari, Italy (2011)
7. Bufarini, S., D'Aria, V., Giacchetti, R.: Il controllo strutturale degli edifici in cemento armato e muratura. EPC Libri srl (2010)
8. Făcăoaru, I.: Non-destructive testing of concrete in Romania. In: Non-destructive Testing of Concrete and Timber, pp. 39–49. Thomas Telford Publishing (1970)
9. NP 137: Normative for In Situ evaluation of the concrete compressive strength of the existing constructions (2014)
10. Samarin, A., Smorchevsky, G.: The non-destructive testing of concrete. Central Research Laboratory. International Technical report, 54 (1973)
11. RILEM NDT 4: Recommendation for in Situ Concrete Strength Determination by Combined Non-destructive Methods. Compendium of RILEM Technical Recommendations, E&FN Spon, U.K., London (1993)
12. Erdal, M.: Prediction of the compressive strength of vacuum processed concretes using artificial neural network and regression techniques. Sci. Res. Essay **4**(10), 1057–1065 (2009)
13. Bellander, U.: NDT testing methods for estimating compressive strength in finished structures–evaluation of accuracy and testing system. In: RILEM Symposium Proceedings on Quality Control of Concrete Structures, Session, vol. 2, pp. 37–45 (1979)
14. Meynink, P., Samarin, A.: Assessment of compressive strength of concrete by cylinders, cores, and non-destructive tests. In: Quality Control of Concrete Structures, Rilem Symposium, Stockholm, Sweden, vol. 1 (1979)
15. Tanigawa, Y., Baba, K., Mori, H.: Estimation of concrete strength by combined nondestructive testing method. Spec. Publ. **82**, 57–76 (1984)
16. Samarin, A., Dhir, R.K.: Determination of in situ concrete strength: rapidly and confidently by nondestructive testing. Spec. Publ. **82**, 77–94 (1984)
17. Gasparik, J., Associazione italiana prove non distruttive monitoraggio diagnostica: Prove non distruttive nell'edilizia. Associazione italiana prove non distruttive (1992)
18. Di Leo, A., Pascale, G.: Prove non distruttive sulle costruzioni in cemento armato. Il Giornale delle Prove non Distruttive Monitoraggio Diagnostica, vol. 4 (1994)
19. GE 039: Guide to the In-Site and Laboratory Determination of the Static and Dynamic Moduli of Elasticity of Concrete. O.M.L.P.T.L. no. 1224/06.09.2001, Romania (2001)
20. Salman, G.A.: Density and ultrasonic pulse velocity investigation of self-compacting carbon fiber-reinforced concrete. Eng. Technol. J. **36**(1), 89–99 (2018)
21. SR EN 12390-13: Testing hardened concrete Part 13: Determination of secant modulus of elasticity in compression (2021)

22. Noguchi, T., Nemati, K.M.: Relationship between compressive strength and modulus of elasticity of high-strength concrete. J. Struct. Constr. Eng **60**, 1–10 (1995)
23. SR EN 12390-3: Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens; ASRO, Romania (2019)
24. SR ISO 5725-1: Accuracy (Trueness and Precision) of Measurement Methods and Results—Part 1: General Principles and Definitions; International Organization for Standardization, Geneva, Switzerland (1994)
25. Bolborea, B., Baera, C., Dan, S., Gruin, A., Burduhos-Nergis, D.D., Vasile, V.: Concrete compressive strength by means of ultrasonic pulse velocity and moduli of elasticity. Materials **14**(22), 7018 (2021)