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EXPERIENCES OF NDT TECHNIQUES TO ASSESS COMPRESSIVE STRENGTH OF THICK REINFORCED CONCRETE STRUCTURES

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ABSTRACT

As compressive strength is used to categorize the concrete in reinforced concrete structures, its monitoring is important for their aging management. The concrete standards and codes regulate the in-situ measurements for checking if the hardened concrete in structure has the compressive strength required by the strength grade of concrete. The compressive strength of concrete can vary regarding the location in the structure. portions of the structure. This variation is partly random and often forced by the factors connected to construction process such as the relative density, the degree of compaction, and the curing conditions. Therefore, the question arises if the compressive strength of concrete including its variation meets the design assumptions for the intended structural lifetime or if the concrete starts limit the operation time.

Non-destructive testing (NDT) methods are helpful for mapping the local variations in concrete strength. A combination of ultrasonic pulse velocity (UPV) and rebound hammer are typical methods for estimating the compressive strength of concrete in situ. Models for estimating compressive strength can be established by calibrating NDT methods with drilled concrete samples. A challenge is to define the minimum number of samples for calibration to guarantee a reasonable accuracy. The factors affecting the accuracy of the strength estimation models include the number of locations for samples, quality of measurements, and the number and types of NDT techniques.

This paper presents the evaluation of concrete strength in situ using a combination of NDT techniques. The investigation was carried out with a mock-up representing a thick reinforced concrete member. The test results show some variation in the compressive strength when applying the combined NDT techniques. Observations of NDT imperfection were consequences of the features of the NDT methods used and difficulties in interpreting their results. The aim of this paper is to share our experiences of the applicability of the NDT applied to the thick concrete structures.

INTRODUCTION

Compressive strength of concrete is the most important single parameter to describe properties of concrete. It represents the mechanical properties of concrete; for example, the 28 days compressive strength of concrete cylinders is the key parameter in most design codes (EN 1992-1-1, 2004). Concrete strength can be determined in the laboratory or from drilled samples but estimating the strength value for hardened concrete in the field remains a challenge (Michalek, 2019).

On-site evaluation of concrete strength is a main challenge in the condition assessment of existing concrete structures. Combined methods involve a combination of NDT methods for predicting the on-site strength of concrete for more comprehensive results. The combination of ultrasonic pulse velocity (UPV) and rebound hammer have been studied by several researchers, and their combined use is reported to improve the accuracy in estimating the compressive strength of concrete (Hannachi and Guetteche, 2012).

This paper summarize the estimation of the compressive strength of thick-walled reinforced concrete mock-up wall representing Nuclear Power Plant NPP containment using combined NDT methods. The mock-up wall of reinforced concrete, presented in Figure 1, is 1.0 m thick, 2.0 m high and 3.5 m long. (Al-Neshawy et. al., 2018).

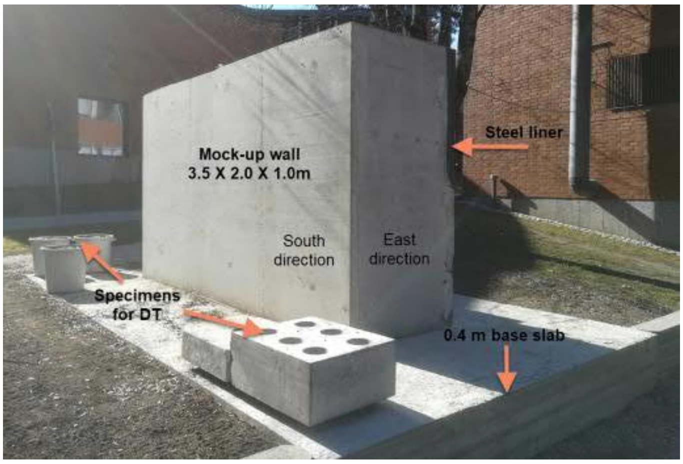

Figure 1 – Overview of the thick-walled concrete structure (Al-Neshawy et. al., 2018).

EXPERIMENTAL PROGRAM

The mix design of the concrete was based on the C35/45 compressive strength class and S3 consistency class. A total of two truck batches were delivered for the casting of the mock-up wall. The mix designs were the same on both batches and average amounts of the realized constituents are shown in Table 1.

Table 1 – Mix design of concretes for C35/45 concrete

Concrete mix		Concrete ingredients (kg/m³)	Aggregates moisture (kg/m³)
Cement (CEM II/B-M (S-LL) 42,5 N)		365	
Aggregates	(0/8 mm)	1045	33.4
	(8/16 mm)	902	8.1
Water	Recycled Water	50	
	Cold Water	102	
Effective water content		170	
Super-plasticizer (Master Glenium SKY 600)		2.74	

Fresh concrete tests were performed during the cast prosess and three cubes (100 × 100 × 100 mm) were prepared for 28 and 91 days compressive strength. The test results of the fresh and hardened concrete are presented in Table 2.

Table 2 – Summary of the fresh and hardened concrete test results.

		Batch I	Batch II
Temperature	[°C]	21	20
Slump	[mm]	170	180
Air content	[%]	3.7	1.0
28d Compressive strength	[MPa]	43	44
91d Compressive strength	[MPa]	51	52

Three samples (100 mm diameter × 100 mm height) were drilled from the concrete structure for confirming the results of the NDT measurements. The average compressive strength of the drilled samples is 53 MPa representing the strength at the age of about 2 years and the average density is 2360 kg/m³.

NON-DESTRUCTIVE TESTING (NDT) METHODS

The original Schmidt (R – value) rebound hammer was used for the measurements. Tests were performed according to (EN 12504-2, 2013). For numerical calculation of the compressed strength from the rebound hammer values, a mathematical function provided by the hammer manufacturer was used (Corbett, 2013).

$$f_c = 0.0115 * (R_{median})^2 + 0.8554 * R_{median} - 12.701 \quad (1)$$

Where f_c is the compressive strength (MPa) and R_{median} is the median R-Value of 9 readings.

For the Ultrasonic Pulse velocity UPV measurements on the mock-up wall, the wall was scanned using 10×10 cm grid area. The measurements were performed in the south surface of the wall every second point except within a distance of 10 cm from the edges (Panzera et. al., 2011). The Ultrasonic Pulse Velocity device (Matest Ultrasonic Pulse Velocity Tester C373N) was calibrated using the calibration reference bar. The calibration was performed each time when the UPV device was used. An ultrasound couplant gel (ZG-F, Ultrasonic Couplant gel, Germany) was used as a coupling material between the concrete surface and the UPV transducers.

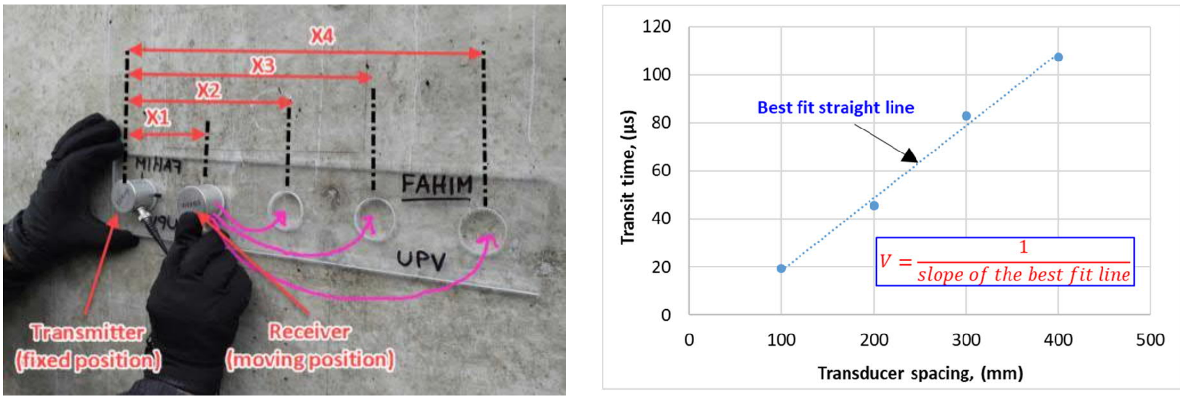

Figure 1. Illustration of the indirect (surface transmission) measurement and example of obtaining the mean pulse velocity.

The measurements were performed using the UPV indirect transmission according to the (EN12504-4, 2004). The pulse velocity based on the indirect transmission was determined by recording the transit times by placing the receiver at different distances (100, 200, 300 and 400 mm) from the fixed position of the transmitter and then obtaining the mean pulse velocity as inverse of slope of a best fit line plotted using spacing versus transit time data.

Drilled cores of 100 cm diameter were retrieved from a concrete slab, as shown in Figure 2, and tested in compression to establish a relationship between the compressive strength estimated by NDT methods and the in-situ strength measured by core testing. The concrete slab was cast concurrently with the mock-up wall using the same concrete. The slab was stored in the same outdoor condition as the mock-up wall.

After extracting of the cores, they were placed inside a curing chamber with temperature of 20±2°C and relative humidity of 95±5%. The cores were sawed into a length of 100 mm and the testing surfaces were grinded and tested in compression in the following day.

Figure 2. Drilling of core from the concrete slab cast of the concrete used in the wall concrete and stored in the same condition.

For evaluating compressive strength of the mock-up wall using ultrasonic pulse velocity, the correlation of pulse velocity and compressive strength values defined by drilled core tests was performed according to (EN 12504-4, 2004). Pulse velocity measurements were performed covering the slab presented in Figure 2 (points A – L) before drilling the core specimens. The cores were cut and tested for strength according to (EN 12540-1, 2019) and a correlation between the drilled cores strength and velocity established, as shown in Figure 3.

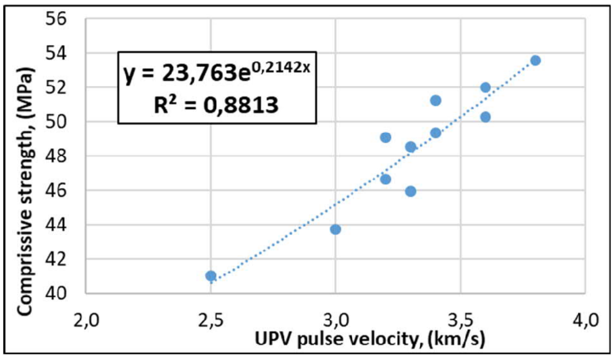

Figure 3. Correlation of pulse velocity and actual compressive strength of the mock-up concrete.

The equation with a R^2 value of 0,88 described in Figure 3 was used to predict the compressive strength f_c (MPa) of the mock-up wall based on the pulse velocity (km/s):

$$f_c = 23{,}763e^{(0.2142V)} \tag{2}$$

A combined of drilled core test results, ultrasonic pulse velocity measurements and rebound number measurements (known as SonReb method) is used to calculate the compressive strength of concrete based on the rebound hammer number and ultrasonic pulse velocity. The basis of SonReb technique is given as tentative recommendations for “in-situ concrete strength estimation by combined non-destructive methods” published by RILEM Committee TC 43 CND, 1983. (Minutolo et al., 2019), (Cristofaro et al., 2012), (IAEA–TCS–17, 2002), (Breysse et al., 2019), (Nobile, 2015) and (Breccolotti & Bonfigli, 2015).

The SonReb equation describing the compressive strength f_c(MPa) as functions of the pulse velocity V (m/s) and the original rebound hummer number R is:

$$f_c = 0{,}32035 \cdot V^{0{,}49282} \cdot R^{0{,}27346} \tag{3}$$

The coefficient of determination R^2 for Equation (3) is 0,8862

NDT RESULTS AND DISCUSSION

The Original Schmidt Rebound Hammer measurements were performed in July 2019 for all the mock-wall surfaces (age of the concrete 2 years). The compressive strength results obtained from the rebound hammer measurements for the south surface of the mock-up wall is represented in Figure 4. As shown in Figure 4, the estimated compressive strength of the lower part of the wall (concrete batch I) is lower than the upper part (concrete batch II). The reason for the difference could be a slightly higher compressive strength of concrete batch II, but the measured 35 MPa difference between the upper and lower part is perhaps too large

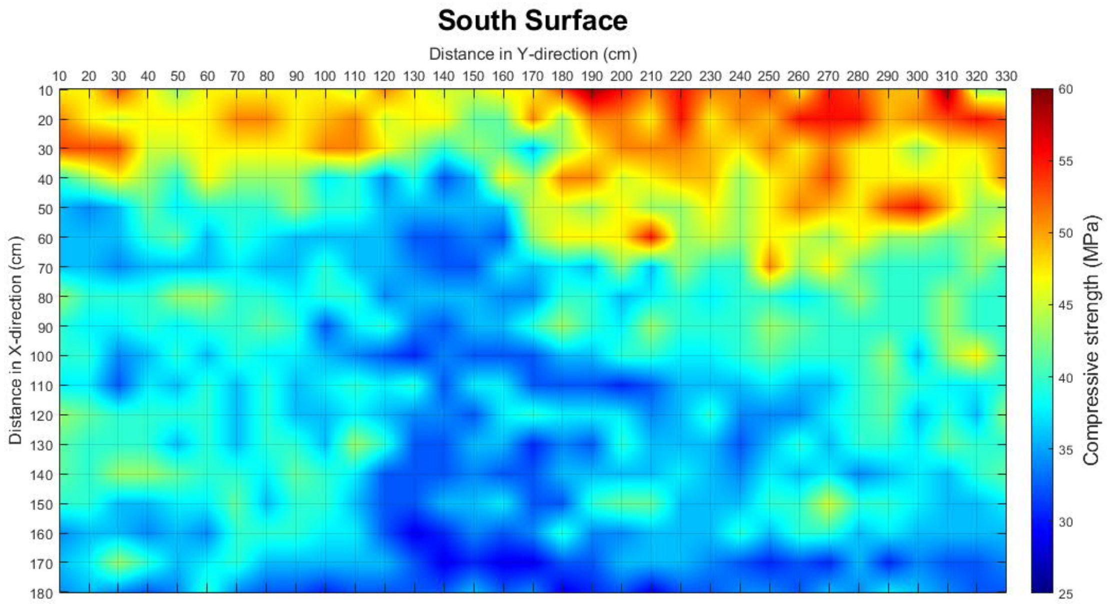

Figure 4. Compressive strength of the south surface of the mock-up wall using R-Value hammer.

The compressive strength obtained from the UPV measurements for the south surface of the mock-up wall are represented in Figure 5. The estimated compressive strength of the lower part of the wall (concrete batch I) is lower than the upper part (concrete batch II) on the south and west surfaces with coefficients of variation of 8,1% and 6,4%, respectively.

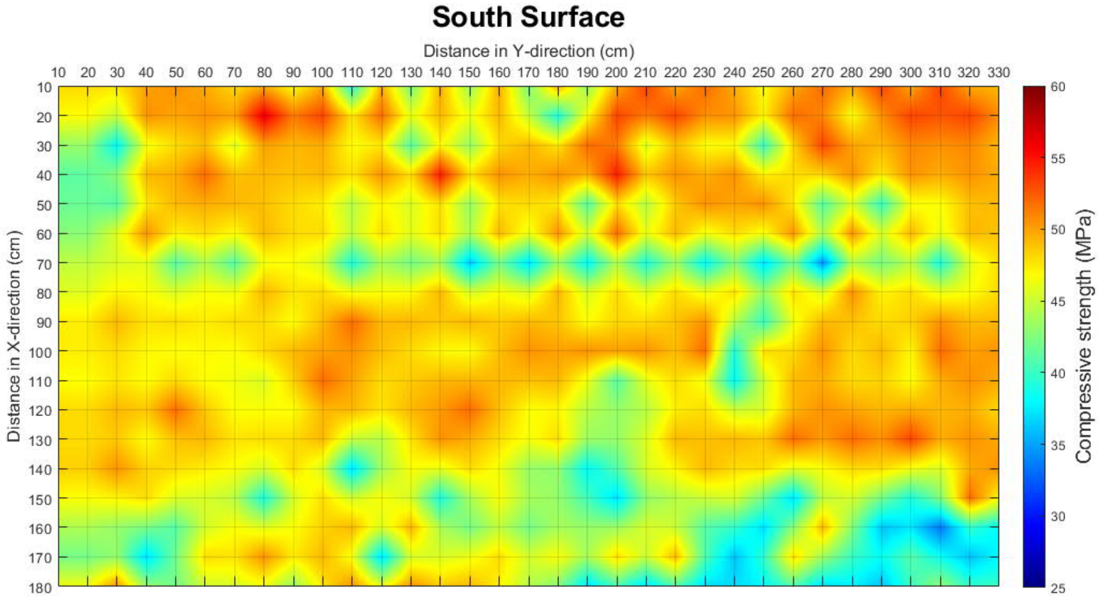

Figure 5. Compressive strength values for the south surface of the mock-up wall based on UPV measurements.

The compressive strength obtained by combining the UPV measurements and the rebound hammer measurements based on the SonReb equation for the south surface of the mock-up wall is represented in Figure 6. The same variation of the compressive strength in the wall is shown in Figure 6, especially in the bottom part at the middle of the wall which could indicate the compaction quality during the casting process and also the variation in the concrete batches.

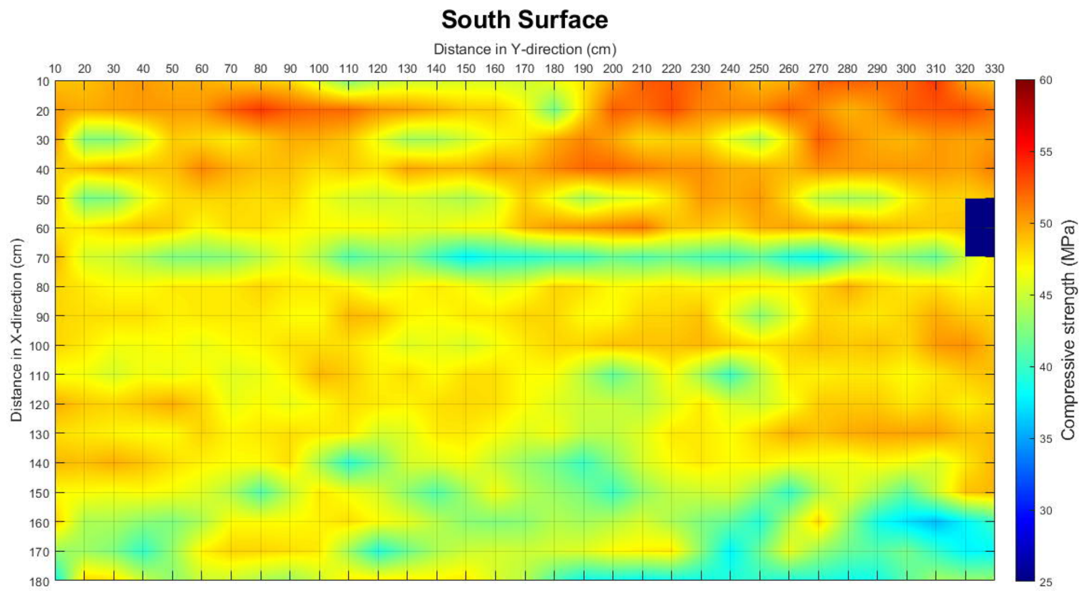

Figure 6. Compressive strength values for the south surface of the mock-up wall received by combining the results of the UPV and rebound hammer measurements.

The improvement of the accuracy of the strength prediction using SonReb method is as shown in Figure 7. For example, the probability of the combination of rebound hammer and ultrasonic pulse velocity results in the peak probability 0.12 of concrete strength, while the probability of detection is 0.07 for rebound hammer and 0.10 for UPV measurements. As presented in Table 3, the standard deviation and coefficient of variation is smaller when using the SonReb calculation method compared to the rebound hammer (R-value) and UPV.

It is very important to notice that the accuracy of each and every relationship depends on the calibration and correlation that is made with destructive tests, i.e., core samples.

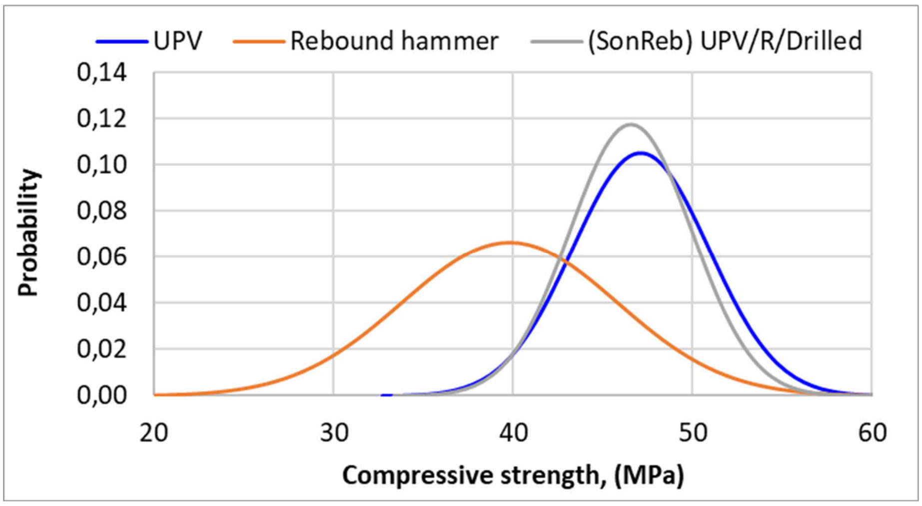

Figure 7. Normal distribution of the concrete compressive strength based on the combined NDT methods.

Table 3. Summary of the estimated compressive strength results based on the combined NDT methods.

	Estimated compressive strength (MPa)		
	R-hammer	UPV	SonReb (UPV/R/Drilled)
Average	40	47	47
Standard Deviation	6,0	3,8	3,4
Coefficient of variation COV (%)	15,1	8,1	7,3
Median	39	48	47
Maximum	59	55	54
Minimum	29	36	36

CONCLUSION

This paper presents the on-site evaluation of concrete strength of thick-walled reinforced concrete mock-up wall representing NPP containment using combined non-destructive testing (NDT) techniques and testing the compressive strength of drilled samples. The combined NDT methods include the use of the original rebound hammer and the ultrasonic pulse velocity UPV device. The estimation of compressive strength using rebound hammer was performed using the hammer converting algorithm provided be the hammer manufacturer, while estimation of compressive strength using UPV was performed using an algorithm based on the destructive testing of drilled cores specimens.

The combined NDT results show a variation in the test results of compressive strength comparing to that of drilled samples. The variation could be related to the empirical algorithm used in the NDT calculations. Non-destructive testing (NDT) offers an interesting approach to estimate the compressive strength of concrete.

- Extracting concrete cores and testing for compressive strength is considered the most reliable solution for evaluating the compressive strength of concrete. Drilling the core specimens is fast procedure, but location and properties (moisture, aggregate content, reinforcement, cracking during the drilling process, etc.) of the cores are affecting the compressive strength results. Coring is not an option for owners of important structures, especially when there are concerns about further damaging the structure.
- The Rebound Value (number) can be used to assess the surface hardness and estimate strength of hardened concrete in situ. The rebound hammer can be used to assess the variation of concrete strength. Generally, the rebound hammer is easy and fast to use for concrete applications in situ, but calibration of the hammers and surface condition of concrete, presence of rebar, presence of sub-surface voids can affect test results.
- Ultrasonic Pulse Velocity (UPV) is an effective method for quality control of concrete materials and detecting damages in structural components. The use of UPV in evaluating of the compressive strength of concrete should be associated with drilling the cores for testing, which is not an attractive option with the critical concrete structures.
- The compressive strength of the concrete using combined UPV, rebound hammer measurements and testing of drilled core specimens (SonReb method) could predict the compressive strength of reinforced concrete structures with a decent accuracy.
- In conclusion, the prediction of compressive strength carried out shows how the use of known destructive methodologies, i.e., core samples, associated with a non-destructive method (SonReb) make it possible to improve the accuracy of the estimation of the concrete compressive strength in situ if the NDT methods are calibrated by using enough test specimens.

REFERENCES

EN 1992-1-1: Eurocode 2: Design of concretestructures - Part 1-1: General rules and rules for buildings (2004).

Hannachi and Guetteche: Application of the Combined Method for Evaluating the Compressive Strength of Concrete on Site. Open Journal of Civil Engineering, 2012, 2, 16-21 doi:10.4236/ojce.2012.21003 (2012).

Al-Neshawy, F, Ojala, T., Ferreira, M., Puttonen, J.: Mock-up wall for non-destructive testing and evaluation of thick reinforced concrete structures in nuclear power plants. 12th European conference on Non-Destructive Testing. June 11-15, 2018 Gothenburg, Sweden, (2018).

EN 12504-2, (2013)Testing concrete in structures - Part 2: Non-destructive testing - determination of rebound number.

Corbett D. (2013) Advancing the Rebound Hammer Method: A New Concrete Test Hammer. In: Güneş O., Akkaya Y. (eds) Nondestructive Testing of Materials and Structures. RILEM Bookseries, vol 6. Springer, Dordrecht

Michałek J. (2019). Variation in Compressive Strength of Concrete aross Thickness of Placed Layer. Materials (Basel, Switzerland), 12(13), 2162. https://doi.org/10.3390/ma12132162.

EN12504-4. (2004). SFS-EN12504-4. Testing Concrete. Part 4: Determination of Ultrasonic Pulse Velocity.

Minutolo, V., Ronza, S. Di, Eramo, C., & Zona, R. (2019). The Use of Destructive and non Destructive Testing 2 in Concrete Strength Assessment for a School Building 4 5. https://doi.org/10.20944/preprints201906.0121.v1

IAEA–TCS–17. (2002). Guidebook on non-destructive testing of concrete structures (Issue 17). https://www-pub.iaea.org/books/iaeabooks/6347/Guidebook-on-Non-destructive-Testing-of-Concrete-Structures

Cristofaro, M. T., D'Ambrisi, A., De Stefano, M., & Tanganelli, M. (2012). Mechanical Characterization of Concrete from Existing Buildings with SonReb Method. 15th World Conference on Earthquake Engineering, 24–28.

Breysse, Denys, Balayssac, J. P., Biondi, S., Corbett, D., Goncalves, A., Grantham, M., Luprano, V. A. M., Masi, A., Monteiro, A. V., & Sbartai, Z. M. (2019). Recommendation of RILEM TC249-ISC on non destructive in situ strength assessment of concrete. Materials and Structures/Materiaux et Constructions, 52(4), 1–21. https://doi.org/10.1617/s11527-019-1369-2

Breccolotti, M., & Bonfigli, M. F. (2015). I-SonReb: An improved NDT method to evaluate the in situ strength of carbonated concrete. Nondestructive Testing and Evaluation, 30(4), 327–346. https://doi.org/10.1080/10589759.2015.1046872

Nobile, L. (2015). Prediction of concrete compressive strength by combined non-destructive methods. Meccanica, 50(2), 411–417. https://doi.org/10.1007/s11012-014-9881-5

Panzera, T., Christoforo, A., Cota, F., Borges, P., Bowen, C., (2011). Ultrasonic Pulse Velocity Evaluation of Cementitious Materials. Advanced Composite Materierals. - Advances in Composite Materials - Analysis of Natural and Man-Made Materials, Pavla Těšinova, IntechOpen, DOI: 10.5772/17167.