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Application of a non-destructive method in the analysis of the homogeneity of a concrete foundation in a tunnel structure

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Abstract: This paper presents the application of the pulse echo test (PET) method at 22 positions of a foundation element with a height of 1.4 m, aiming at a non-invasive assessment of the quality of the produced concrete. Additional verification was carried out through destructive testing by coring at positions 1 and 21, where the parameters of bulk density, moisture content, porosity, and compressive strength were analyzed. Correlation analysis indicated a negative relationship between porosity and strength, as well as between moisture content and strength, with a high reliability of the regression relation ($R^2 \approx 0.85$). Despite the limitations of the PET method for shorter elements, proper calibration and combination with destructive procedures allow for reliable interpretation. The obtained results confirm the stability of the reflectograms, uniform pulse velocity, and mechanical integrity of the concrete mass, thereby confirming the technical validity of the foundation and the applicability of the methodology in similar infrastructure projects.

Key words: non-destructive methods, tunnel, ultrasonic testing, PET method, destructive testing

Primjena nedestruktivne metode u analizi homogenosti betonskog temelja tunelske konstrukcije

Sažetak: U ovom je radu prikazana primjena metode impulsne refleksije (PET) na 22 pozicije temeljnog elementa visine 1,4 m, s ciljem neinvazivnog ocjenjivanja kvalitete izvedenog betona. Dodatna verifikacija izvršena je destruktivnim ispitivanjem putem kernovanja na pozicijama 1 i 21, gdje su analizirani parametri zapreminske mase, vlažnosti, poroznosti i tlačne čvrstoće. Korelacijska analiza ukazala je na negativnu vezu između poroznosti i čvrstoće, kao i između vlažnosti i čvrstoće, uz visoku pouzdanost regresijskog odnosa ($R^2 \approx$ 0.85). Unatoč ograničenjima PET metode kod kraćih elemenata, pravilna kalibracija i kombiniranje s destruktivnim postupcima omogućuju pouzdanu interpretaciju. Dobiveni rezultati potvrđuju stabilnost reflektograma, ujednačenu brzinu impulsa i mehaničku ispravnost betonske mase, čime se potvrđuje tehnička valjanost temelja i primjenjivost metodologije u sličnim infrastrukturnim projektima.

Ključne riječi: nedestruktivne metode, tunel, ultrazvučno ispitivanje, PET metoda, destruktivna ispitivanja

1. INTRODUCTION

The rapid development of urban areas in recent decades has increased the need for more efficient use of underground space [1–3]. Tunneling is a complex and interdisciplinary process [4–7] that involves not only design and construction, but also comprehensive quality control of the constructed elements, particularly in the context of structural safety and long-term functionality of structures.

In modern construction practice, especially in the field of underground infrastructure, reliable assessment of the quality of concrete elements is a crucial step in the verification of structures [8]. Foundations of tunnel structures pose a particular challenge, as access to the structure is restricted, and the possibilities of destructive testing are technically and logistically minimized. In such circumstances, the application of non-destructive testing methods becomes necessary, not only for preserving the integrity of the structure, but also due to the need for rapid, spatially continuous and cost-effective analysis of structural homogeneity [9-11].

Non-destructive methods provide insight into the internal structure of concrete elements without physical damage, thus eliminating the need for additional repairs, interruptions in construction work or complicated logistical interventions. Their application is especially suitable in the stages of technical control, when it is necessary to confirm that the constructed elements meet the designed requirements in terms of homogeneity, compactness and structural uniformity [12]. In this context, non-destructive methods are not an alternative to destructive techniques, but rather a complementary tool that enables spatial interpolation between point results obtained by coring, and the identification of potential irregularities that could remain unnoticed in conventional visual inspection [13,14].

As part of the Kobilja Glava tunnel construction project, which is carried out in an urban area under complex geotechnical conditions, and is part of the connection of Vogošća with Sarajevo and the traffic connection of the city center with the A1 highway on Corridor Vc, there was a need to assess the homogeneity of the concrete foundation. Due to the limited access to the foundation zones, a non-destructive pulse analysis method was applied with the aim of spatially assessing structural uniformity without compromising the integrity of the structure. In this particular case, the contractor had at their disposal a PET (Pile Echo Test) system that was in good technical order, calibrated, and verified for field use. The choice of this method was not motivated solely by its cost-efficiency, but primarily by the fact that the PET instrument was the only available option at the time of control, which enabled a timely and functional analysis without additional costs or delays [15].

The application of the pulse method enabled the generation of spatially continuous data on the reflectivity and internal structure of the concrete foundation, along with the detection of zones with potential deviations in homogeneity [16]. The obtained results were correlated with previously performed coring, thus ensuring validation of the method and confirming its reliability in specific conditions [17].

In a wider context, this example confirms that non-destructive methods, when properly applied and subjected to technical control, can serve as an effective tool for assessing the quality of constructed concrete elements. Their application does not require special field preparations, does not damage the integrity of the structure, and enables quick decision-making based on reliable data. Unlike destructive methods that provide information limited to individual testing points, non-destructive methods provide insight into the structural properties of the material in the entire volume of the element, which significantly increases the reliability of the assessment. In this sense, pulse analysis of concrete, as a representative of non-destructive methods, shows great potential for integration into standard technical control protocols, with the possibility of adaptation to the specifics of individual projects [18,19].

This paper presents the application of a non-destructive method for analyzing the homogeneity of the concrete foundation of the tunnel structure, with a focus on technical implementation, interpretation of results, correlation with destructive tests, and formal data processing. The objective is to demonstrate the methodological justification for applying pulse analysis under real-world conditions, and to confirm its functionality as a reliable tool for the systematic quality assessment of concrete infrastructure elements.

2. METHODOLOGY

The methodology of this research defines the technical procedure for applying the non-destructive pulse analysis method (PET) to the concrete foundation of the tunnel structure, with strict control of measurement conditions, instrumentation and data processing, as well as validation of the results using destructive methods.

2.1. Applied method

In this research, the Pile Echo Test (PET) method was used to assess the homogeneity of the concrete foundation of the tunnel structure. The test was conducted in accordance with the ASTM D5882-16 standard [20], which ensures the application of a validated procedure and the reliability of the obtained results.

The method is based on the generation of a mechanical pulse, while the reflected waves are recorded in the time domain. Reflections occur at the boundaries of layers with different densities and elasticities, which enables the identification of internal irregularities such as voids, segregation and zones of poor compaction [21,22].

For the purpose of testing pile integrity, the Piletest PET (Pile Echo Tester), model PET Pro USB, manufactured by Piletest Ltd. (Israel) was used. The instrument uses a high-sensitivity accelerometer integrated into the sensor unit (measurement range ±50 g, frequency response 0–10 kHz). The excitation was performed using an impact hammer with a mass of 500 g. The signal from the sensor is transmitted via a waterproof USB mini cable to a recording and processing device, where the reflected pulse is registered and graphically displayed. The device is calibrated to an accuracy of ±5%, and all data is automatically stored for subsequent analysis.

A total of 22 positions of the concrete foundation element with a height of approximately 1.4 m were tested. A handheld hammer with a metal impact plate was used to generate the pulses, while the response of the reflected signals was registered by a high-sensitivity accelerometer connected to a portable digital analyzer.

2.2. Location and terrain preparation

The tests were carried out as part of the works on the Kobilja Glava tunnel, in the right tunnel tube, on the right side, on the foundation marked as DK13/A. The location was selected based on the specific geotechnical conditions and technical requirements of the project.

Before starting the measurement, the surface was prepared, which included the removal of dust, laitance, formwork remains and free particles, as well as a detailed visual inspection to detect possible surface irregularities. At the measurement points, the concrete surface was additionally cleaned and coated with a thin layer of petroleum jelly to improve the pulse transmission between the sensor and the concrete mass. This procedure ensured high-quality sensor contact, minimized the energy loss of reflected waves, and enabled a clear response in the time domain [23,24].

The test locations were marked in a regular grid, which ensured the spatial uniformity of the collected data. Special attention was paid to ensuring a stable contact connection between the sensor and the concrete surface, which is a key factor for the reliability of the obtained results [25].

During the test, the air temperature ranged between 18 °C and 22 °C, with a relative humidity of about 60%. The conditions were stable, without direct exposure to sunlight, which eliminated the impact of temperature gradients on the concrete surface. The values were recorded in a field diary and used as a reference when analyzing the response signals, in order to ensure the consistency and technical reliability of the results. Figure 1 shows the layout of test points on the foundation DK13/A.

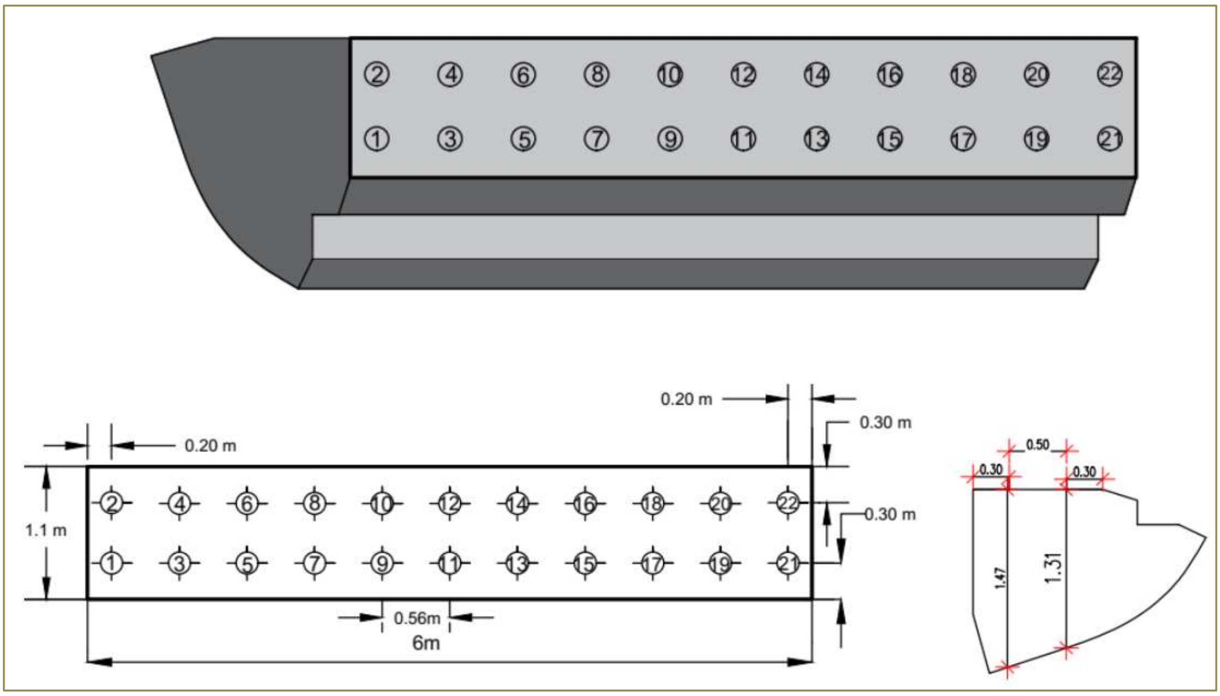

Figure 1. Layout of test points - DK13/A, PET method [made by authors].

2.3. Measurement protocol

Measurements were made at points distributed in a regular grid, with an average spacing of 0.5 to 0.6 meters. At least three repeated impacts were performed at each point, and the average result was used for analysis. This procedure minimized the influence of random deviations and ensured data consistency [26].

The measurement process was monitored in real time, and the reflected signals were immediately reviewed to check their quality. In case of deviation or noise, the measurement was repeated at the same point. Recording and signal processing were conducted using the software package PET Win 8.5, which enables digital acquisition, filtering and interpretation of reflected pulses in real time. In order to eliminate noise and improve the signal-to-noise ratio, a band-pass filter in the frequency range of 200–3000 Hz was applied, which corresponds to typical values for concrete piles up to 20 meters long. The software automatically normalizes the amplitudes and determines the echo time based on the first significant reflected pulse. The analysis is based on the identification of the travel time of reflected waves, reflection amplitudes, frequency analysis and the attenuation coefficient. These parameters enable the assessment of the homogeneity of the concrete mass and the detection of potential irregularities [27].

The measurement principle is based on the induction, propagation, reflection and reception of waves. The waves are initiated by a hammer blow, and their velocity through the material can be determined according to the expression [28]:

$$v = \sqrt{\frac{E}{\rho}} \quad (1)$$

where:

- v - is the wave velocity (m/s),
- E- modulus of elasticity of concrete (Pa),
- ρ- material density (kg/m^3).

Knowing the wave velocity and the travel time to the reflecting surface, the depth of the defect or the end of the pile can be calculated as [28]:

$$L = \frac{v \cdot t}{2} \quad (2)$$

where:

- L - is the depth of the defect or the end of the pile (m),
- v - velocity of the wave through the material (m/s),
- t- travel time of the wave to the reflecting surface (s).

Figure 2 shows a field measurement segment at one of the test points, with clearly visible measurement equipment and operators during data collection and control.

Figure 2. A view of the measurement process at one of the test points [photo by authors].

2.4. Correlation with destructive testing

To confirm the results of the non-destructive method, coring was performed at selected points of the foundation, at positions 1 and 21, shown in Figure 1. The cores were extracted to a depth of 1.2 meters, with the aim of determining the homogeneity of the concrete, the presence of segregations, voids, as well as for laboratory testing of compressive strength.

The obtained samples were visually analyzed, and their structure was compared with the reflective profiles obtained by PET measurements. The concrete samples were prepared and tested in accordance with the requirements of the standard EN 12504-1 [29], which prescribes laboratory testing procedures for assessment of the mechanical characteristics of concrete.

All relevant parameters required for assessing the quality of concrete were determined in the laboratory: porosity, water absorption and compressive strength. The results of laboratory tests were then compared with signals obtained by the PET method, which enabled detailed validation of the non-destructive analysis [21,27]. Figure 3 shows the collection of core samples from locations 1 and 21 (shown in Figure 1) and their preparation for laboratory tests.

Figure 3. Collection of core samples from locations 1 and 21 and preparation for laboratory tests [photo by authors].

3. RESULTS AND DISCUSSION

As part of the investigation of the quality of the Kobilja Glava tunnel foundation, combined tests were conducted using the non-destructive PET method and destructive laboratory analysis of samples obtained by coring. The goal was to determine the homogeneity of the concrete mass, identify any local irregularities, and confirm the reliability of the indirect method through correlation with the mechanical parameters of the concrete.

3.1. PET tests

The PET method was applied to a total of 22 positions (see Figure 1) along the longitudinal axis of the foundation. An identical pulse propagation velocity of 4350 m/s was registered at all points, with stable reflectograms and clearly defined reflection. The amplitudes of the reflected signals ranged from 16 to 18 A, while the number of repeated blows per point ranged between 3 and 5, where the average results were used for analysis.

Figure 4 shows the characteristic response of the PET method at positions 1 and 21 (Figure 1), along with the identification of reflected pulses and signal stability.

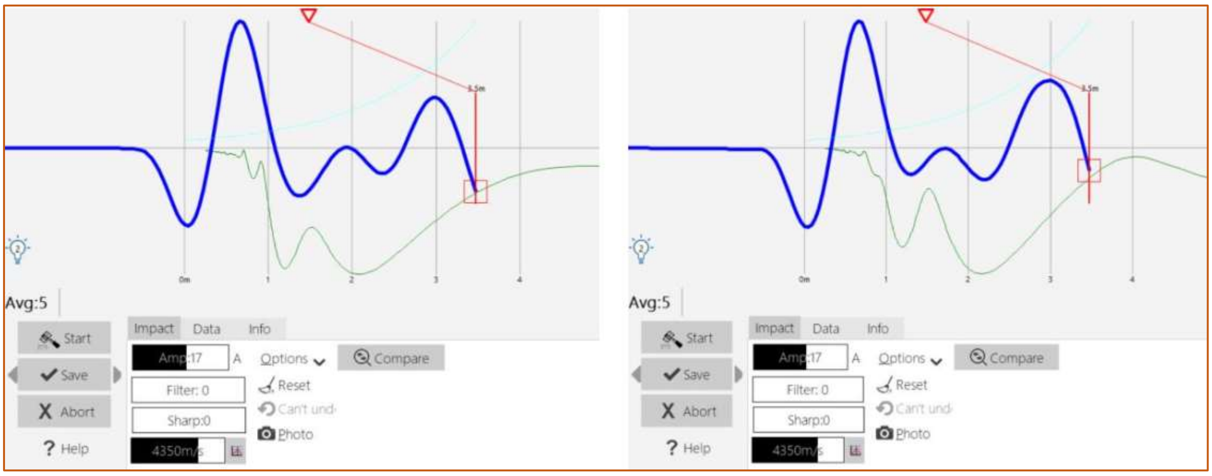

Figure 4. Reflectograms recorded by the PET method at positions 1 and 21 – pulse response and amplitude stability.

3.2. Destructive analysis

At positions 1 and 21 (see Figure 1) samples were collected by coring for laboratory analysis of the physical and mechanical properties of the concrete mass. A total of four samples were tested, two from each position.

Laboratory processing included the determination of bulk density, moisture content, porosity and compressive strength. The tests were carried out in accordance with applicable standards, using standardized procedures for processing and interpreting the results.

Table 1 shows the individual results for each sample, including their dimensions, mass, calculated volume, bulk density, water content, degree of porosity, and the determined compressive strength with correction according to the homogeneity factor.

Table 1. Results of laboratory testing of concrete samples

Test location	Sample dimensions (mm)		Sample mass (gr)	Volume (m^3)	Bulk density (kg/m^3)	Moisture content W (%)	Porosity P (%)	Determined compressive strength of the sample (MPa)	
	d	h						fck,is	fck,is/0.85
Position 1	92.7	100.0	1530	0.67	2268	1.6	7	31.6	37
Position 1	92.7	100.0	1533	0.67	2273	1.6	7	32.0	38
Position 21	92.7	100.0	1555	0.67	2305	1.5	6	32.5	38
Position 21	92.7	100.0	1554	0.67	2304	1.5	6	32.8	39

Where fck,is is the value determined on the specific sample, and fck,is/0.85 is the correction in accordance with the standard relationship between the test shape of the sample and the designed reference value.

The test results show that the compressive strength values range from 31.6 to 32.8 MPa, which is above the designed value of 30 MPa. The porosity ranges between 6% and 7%, while the moisture content is stable and low (1.5%–1.6%), which indicates favorable conditions for hardening and preserving the concrete structure. The observed deviations are minimal and do not affect the functionality of the foundation.

Figure 5 shows the correlation between the measured compressive strength and porosity of the samples. It is evident that the increase in porosity leads to a slight decrease in strength, but all samples remain within the acceptable range, without significant deviations from the designed values.

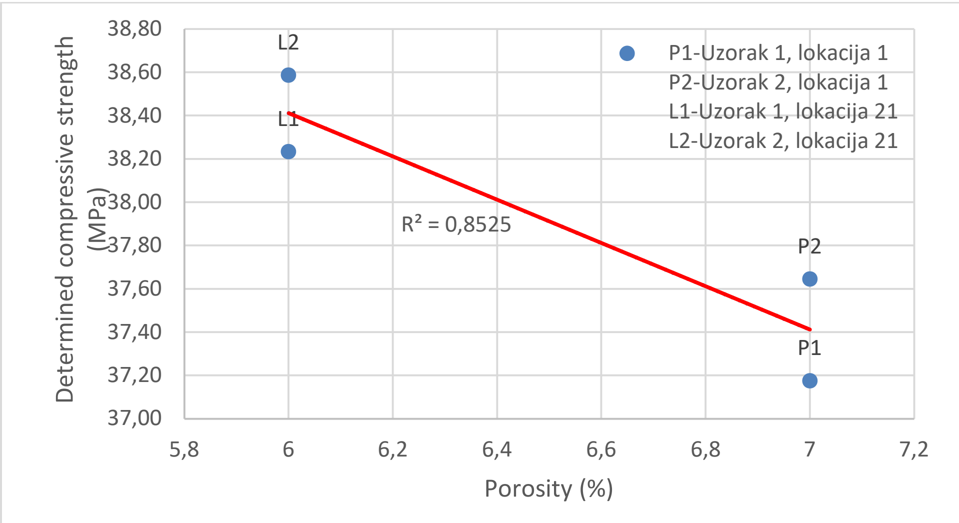

Figure 5. Correlation between compressive strength and porosity of concrete samples – positions 1 and 21

Figure 6 below shows the relationship between the moisture content of the samples and their compressive strength, showing a clear trend that confirms the influence of moisture on the mechanical properties of concrete.

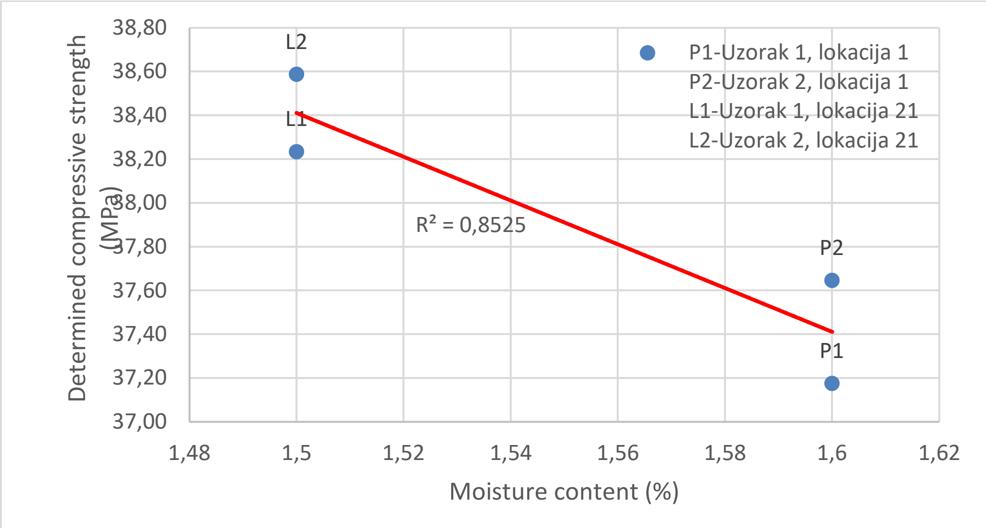

Figure 6. Correlation between compressive strength and moisture content of concrete samples – positions 1 and 21

Analysis of samples from positions 1 and 21 indicates a pronounced negative correlation between moisture content and compressive strength, as well as between porosity and compressive strength. In both cases, an increase in moisture and porosity is consistently associated with a decrease in strength. The obtained regression relationship ($R^2 \approx 0.85$) confirms the high reliability of the observed trend, which is in line with the expected behavior of concrete in dry and compact conditions. Such a relationship can be used as a reference criterion for quality control in laboratory and field analyses.

A combined analysis of the PET results and laboratory tests indicates a consistency in the quality of the constructed foundations. The reflectograms are stable, with no signs of discontinuities, while the physical and mechanical parameters of the samples confirm that the concrete mass is homogeneous, compact and in accordance with the design requirements. The methodological approach, which includes non-invasive field analysis and destructive laboratory verification, proved to be effective in assessing the condition of the foundation without the need for additional interventions or delays.

3.3. Limitations of the PET method

The pulse echo test (PET) method is typically applied to piles longer than 4 m, but recent technical experiences indicate that reliable responses can also be obtained for shorter concrete elements with proper calibration and optimization of the impact energy [30,31]. Frequency analysis, sensor selection and pulse spectrum control enable its application to foundation elements shorter than 2 m, provided that sufficient response in the time domain is ensured.

In order to confirm the validity of the PET method results, a combination with destructive testing by coring is often used, where the physical and mechanical properties of the core are analyzed: density, homogeneity, strength and the presence of voids [32,33]. Comparison of the results allows the verification of the foundation quality and increases the reliability of the assessment of the structure's condition.

However, the application of the PET method to shorter elements requires additional attention in interpretation, especially in the presence of complex boundary conditions, multilayer materials or local inhomogeneities. Reflectograms can be more sensitive to surface irregularities, and the amplitude response can vary depending on the geometry and contact area. In such cases, additional analysis by low-frequency methods or direct verification by sampling is recommended.

4. CONCLUSION

This paper presents the application of the PET method to 22 test positions of a 1.4m high foundation element, with additional destructive testing by coring at positions 1 and 21. The goal of the research was to assess the quality of the constructed foundation based on the pulse propagation velocity, response amplitude and physical and mechanical properties of the concrete mass. The obtained results indicate a stable reflectogram, homogeneous concrete structure, low porosity and compressive strengths above the designed values.

Correlation analysis showed a pronounced negative relationship between porosity and strength, as well as between moisture content and strength, with a high reliability of the regression relationship ($R^2 \approx 0.85$). These relationships confirm the expected behavior of concrete in compact and dry conditions, and enable a quantitative assessment of the quality of the constructed elements. Comparison of the results of the PET method and cored samples confirms the technical validity of the reflected data and increases the reliability of the structural condition assessment.

Despite the limitations of the PET method for shorter elements, proper calibration, impact energy optimization, and additional verification through sampling allow for reliable interpretation. The methodological approach applied in this study has proven to be effective and applicable in infrastructure projects where rapid, non-invasive, and multi-layered foundation diagnostics are required.

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