*Marko Stojanović[1], Miloš Vasić[*1], Anja Terzić[1], Filip Pantelić[2], Aleksandar R. Savić[3], Ksenija Janković[1], Simon Sedmak[4]*

NON-DESTRUCTIVE ESTIMATION OF COMPRESSIVE STRENGTH OF LONG-TERM AGED CONCRETE BASED ON DYNAMIC ELASTIC MODULUS

NEDESTRUKTIVNA PROCENA PRITISNE ČVRSTOĆE DUGOTRAJNOG STARENJA BETONA NA OSNOVU DINAMIČKOG MODULA ELASTIČNOSTI

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 15.06.2026
https://doi.org/10.69644/ivk-2026-02-0255
Adresa autora / Author's address:
[1] Institute for Testing of Materials-IMS, Belgrade, Serbia
M. Stojanović https://orcid.org/0000-0003-1804-5138 ;
M. Vasić https://orcid.org/0000-0002-5743-6038 ;
A. Terzić https://orcid.org/0000-0002-4762-7404
K. Janković https://orcid.org/0000-0003-3744-3799
[2] Academy of Technical and Art Applied Studies, Belgrade, Serbia
F. Pantelić https://orcid.org/0000-0003-4653-9901
[3] University of Belgrade, Faculty of Civil Engineering, Belgrade, Serbia A.R. Savić https://orcid.org/0000-0002-1777-6775
[4] Innovation Centre of the Faculty of Mechanical Engineering, Belgrade, Serbia S. Sedmak https://orcid.org/0000-0002-2674-541X
*email: milos.vasic@institutims.rs

Keywords
- non-destructive testing
- static and dynamic modulus
- compressive strength
- air-entrained concrete
- rubberised concrete

Abstract

This study investigates the applicability of non-destructive testing for estimating the compressive strength of concrete after long-term aging. Three concrete mixtures are analysed: reference concrete, air-entrained concrete, and rubberised concrete, all produced with a constant water-cement ratio of 0.40. Compressive strength is experimentally determined at 3, 7, 28, and 90 days, while the dynamic elastic modulus is obtained after approximately 803 days using a resonance-based non-destructive method. The long-term compressive strength is then estimated from the measured modulus using an established modulus-strength relationship. In addition, bulk density and air-void system parameters are analysed to support the interpretation of results. The air-entrained concrete exhibits a developed system of fine and uniformly distributed air voids, while the rubberised mixture contains a deformable low-density phase due to the presence of rubber particles.

The results indicate that the modulus-based estimation provides physically consistent trends; however, its accuracy depends on the internal structure of concrete. The reference concrete shows an increase in estimated strength after long-term aging, while the air-entrained and rubberised mixtures exhibit deviations related to their modified pore structure and phase composition. The study demonstrates that non-destructive evaluation based on dynamic elastic modulus can be applied for long-term strength assessment, but calibration of the modulus-strength relationship is necessary for different types of concrete.

Ključne reči
- ispitivanja bez razaranja
- statički i dinamički modul
- čvrstoća na pritisak
- beton sa uvučenim vazduhom
- gumirani beton

Izvod

Ova studija istražuje primenljivost ispitivanja bez razaranja za procenu pritisne čvrstoće betona nakon dugotrajnog starenja. Analizirane su tri betonske mešavine: referentni beton, beton sa uvučenim vazduhom i gumirani beton, sve proizvedene sa konstantnim odnosom voda-cement od 0,40. Čvrstoća na pritisak je eksperimentalno određena nakon 3, 7, 28 i 90 dana, dok je dinamički modul elastičnosti dobijen nakon približno 803 dana korišćenjem IBR metode, zasnovane na rezonanciji. Dugoročna čvrstoća na pritisak je zatim procenjena iz izmerenog modula korišćenjem utvrđenog odnosa modul-čvrstoća. Pored toga, analizirani su parametri gustine zapremine i sistema vazdušnih šupljina kako bi se podržala interpretacija rezultata. Beton sa uvučenim vazduhom pokazao je razvijen sistem finih i ravnomerno raspoređenih vazdušnih šupljina, dok je gumirana mešavina sadržala deformabilnu fazu niske gustine zbog prisustva čestica gume.

Rezultati ukazuju da procena zasnovana na modulu pruža fizički konzistentne trendove; međutim, njena tačnost zavisi od unutrašnje strukture betona. Referentni beton je pokazao povećanje procenjene čvrstoće nakon dugotrajnog starenja, dok su mešavine sa uvučenim vazduhom i gumirane mešavine pokazale odstupanja u vezi sa modifikovanom strukturom pora i faznim sastavom. Studija pokazuje da se IBR procena zasnovana na dinamičkom modulu elastičnosti može primeniti za dugotrajnu procenu čvrstoće, ali je kalibracija odnosa modul-čvrstoća neophodna za različite vrste betona.

INTRODUCTION

Annually, approximately 1.5 billion waste rubber tyres (WRT) are generated worldwide, contributing to the existing accumulation of tyres in stockpiles and landfills /1/.

The figure 2,135 million tons is specifically mentioned in a 2025 research publication as referring to 2020 total waste statistics from Eurostat /2/. According to data from the Serbian Environmental Protection Agency (SEPA), between 2011 and 2021, 380,000 tons of tyres are set on the market, with nearly 50,000 tons of scrap tyres managed in compliance with legislation, while only approximately 500 tons are disposed of in landfills. The Waste Disposal Regulation prohibits landfill disposal of tyres due to their prolonged degradation period (50-80 years). WRT is classed as a separate waste stream, alongside batteries, waste oils, and electrical waste, requiring specialised management standards that include collection, transportation, and treatment. The Rulebook on Waste Tyre Management states that no more than 20 % of collected waste tyres from the previous year may be used for energy recovery, with a minimum of 80 % mandated for recycling, /3/.

The increasing volume of waste tyres, along with the lack of a coordinated processing and recycling infrastructure, present major obstacles to effective management. Heightened global environmental awareness has prompted stringent regulatory measures to mitigate excessive stockpiling and landfill disposal. In Serbia, the management of scrap tyres is financed under the ‘polluter pays’ principle, whereby producers and importers of materials that become waste streams contribute fees to support the waste management system. Pneumatic tyres primarily comprise rubber, steel, and textile components, whose physical and chemical properties remain largely unchanged post-use. Steel wires are repurposed as micro-reinforcements in construction foundries, while textiles find applications as insulation materials or fuel sources, /4/. Given the pressing global and local demand for innovative waste rubber solutions and a favourable legislative environment, this study aims to develop sustainable concrete incorporating WRT, designed to exhibit durability and resilience under extreme atmospheric conditions while adhering to net-zero and circular economy principles through the use of recycled raw materials.

The application of WRT in civil engineering has been under investigation for over three decades. The construction sector has enabled the sustainable reutilisation of WRT, which otherwise would have been discarded or landfilled, adversely impacting environmental and societal well-being /5-7/. Two primary recycling techniques are employed for WRT: ambient and cryogenic size reduction /8, 9/. Resultant WRT-derived products are categorised by size as cuts (> 300 mm), shreds (50-300 mm), chips (10-50 mm), granulates (1-10 mm), powder (< 1 mm), and fine powder (< 500 μm) /5, 10, 11/. Tyre composition significantly influences the properties of recycled products; therefore, thorough evaluation of physico-chemical characteristics prior to recycling is essential to mitigate environmental risks /12, 13/. Optimal WRT disposal strategies emphasise the reuse of crumb rubber (CR) and rubber aggregates (RA) in concrete and asphalt mixtures, whereas energy recovery methods such as incineration are least preferred due to pollution concerns. Beyond concrete and asphalt production, WRT finds applications in geotechnical engineering (e.g., soil stabilisation), pavement systems as sand replacements, and tyre bales employed in gravity retention systems, /14-17/.

Compared to conventional concrete, the incorporation of CR, commonly referred to as rubberised concrete (RC), has demonstrated enhanced freeze-thaw resistance. The use of CR contributes to improved sustainability by reducing life-cycle costs through diminished maintenance requirements over the service life of RC /18-19/. Studies investigating partial replacement of fine aggregates with CR in high-strength concrete have reported increased resistance to acid attack and chloride ion permeability, endorsing RC for maritime construction applications /20, 21/, although some contradictory findings exist /22/. Additionally, the inclusion of rubber granulates or fillers enhances thermal resistance, reducing the demand for interior heating and lowering CO_2 emissions. This thermal insulation capability also mitigates shrinkage and cracking tendencies while improving impact resistance and energy absorption relative to conventional concrete /23/. Despite these benefits, challenges persist due to the inherently weak bonding between rubber particles and cement paste, resulting in reduced composite strength /24, 25/. Surface chemical treatments of rubber particles, including the application of silane coupling agents or water-repellent admixtures, have been employed to improve interfacial adhesion /26, 27/. While extensive research has been conducted on the mechanical and durability performance of WRT-modified concretes /28, 29/, there is still a scarcity of studies that elucidate the microstructural interactions between rubber and cement and their impact on the combined physical, structural, and durability properties investigated using non-destructive testing methods.

In material testing, identifying optimal sampling locations is essential to minimise damage to both the materials and the site /29/. Compliance with applicable legislation requires the use of non-destructive testing (NDT) methods to preserve material integrity /30-32/. The elastic modulus is a fundamental mechanical property in civil engineering, providing critical insights into material behaviour under applied loads. There are two primary types of elastic moduli: static and dynamic, each offering distinct perspectives depending on the testing methodology and objectives. The static modulus, derived directly from stress-strain measurements, is inherently destructive. It exhibits a strong correlation with compressive strength and is integral to structural stability evaluations. In contrast, dynamic modulus measurements are obtained through standardised procedures that combine elastic-wave velocity and density assessments. These methods are non-destructive, applying minimal strain amplitudes to maintain material elasticity /33-36/. Differences between static and dynamic elastic moduli in cement-based materials are attributed to variations in measurement techniques and the multiphase nature of concrete. Static testing typically involves higher strain rates, facilitating the detection of micro-cracking not observable in dynamic tests conducted at lower strain rates /37/. Conversion equations relating static and dynamic moduli have been proposed by Lyndon and Balendran /38/ and are incorporated in British Standards CP 110-1:1972 /39/. Moreover, design codes such as Eurocode 2 and ACI 318 include predictive models for compressive strength based on elastic modulus values /40, 41/. Resonant frequency methods commonly employ accelerometers as sensors; however, their wider application is limited by susceptibility to environmental noise, signal distortion due to sensor mass, and challenges related to sensor cost and attachment /42/. Accurate measurements necessitate precise specimen geometries, typically prisms or cylinders, to minimise acoustic radiation and optimise test results, as specified in ASTM E 1876-01 and ASTM C215 standards. Parameters such as hammer impact duration and specimen length-to-diameter ratio significantly influence outcomes and concrete strength estimations /43, 44/.

This study builds upon established empirical relationships between Young's modulus, shear modulus, and porosity, focusing on the ratio of these moduli to address variability in the absolute values of nearly pore-free materials. Porosity estimation for each specimen is conducted through nonlinear fitting, utilising a correlation constant ratio of 0.5 alongside experimentally derived data. To ensure comprehensive characterisation, representative materials, including normal concrete, aerated concrete, and rubberised concrete, are selected. Advanced measurement techniques, such as ultrasonic wave propagation analysis and resonant acoustic methods combined with accelerometer sensors, are employed to evaluate structural integrity and dynamic behaviour. These state-of-the-art methodologies provide detailed insights critical for applications in construction.

Although non-destructive testing methods based on dynamic elastic modulus are widely used for conventional concrete, their applicability to modified concrete systems remains uncertain. In particular, the presence of entrained air and rubber particles alters the internal structure of concrete, affecting wave propagation and dynamic response. As a result, the established relationships between elastic modulus and compressive strength may not be directly applicable to air-entrained and rubberised concrete.

Despite extensive research on rubberised concrete and air-entrained concrete, there is a lack of studies that evaluate the reliability of modulus-based strength estimation for such materials, especially after long-term aging. The combined influence of internal structure, moisture condition, and material heterogeneity on non-destructive strength estimation is not sufficiently clarified.

Therefore, the aim of this study is to assess the applicability of a modulus-based non-destructive approach for estimating the compressive strength of reference, air-entrained, and rubberised concrete after long-term aging. The results are analysed with respect to differences in internal structure and their influence on dynamic modulus and strength estimation.

MATERIALS AND METHODS

The experimental programme is carried out on concrete mixtures produced using ordinary Portland cement CEM I 42.5R, natural river aggregate, recycled crumb rubber, water, and chemical admixtures. The aggregate consisted of fractions 0/4, 4/8, and 8/16 mm, with an approximate density of 2600 kg/m^3. Crumb rubber obtained from waste tyres, with a particle size of 0/1 mm, is used as an alternative fine aggregate material. Workability is adjusted using a polycarboxylate-based superplasticiser, while an air-entraining admixture is applied to introduce a controlled system of microscopic air voids. All mixtures are produced using potable water.

The investigation includes three types of concrete: a reference mixture, an air-entrained mixture, and a mixture containing rubber particles. In all cases, the water-to-cement ratio is kept constant at 0.40, with a cement content of 360 kg/m^3. The mixtures are proportioned to achieve S4 consistency, determined in accordance with EN 12350-2 and classified according to EN 206. The modification of the internal structure is achieved either by the addition of an air-entraining admixture or by partial substitution of fine aggregate with crumb rubber.

Prismatic specimens measuring 100×100×400 mm are cast for non-destructive testing, with six specimens prepared for each mixture. Compressive strength is determined on specimens at ages of 3, 7, 28, and 90 days. The long-term behaviour is evaluated by conducting non-destructive measurements after approximately 803 days of storage under laboratory conditions.

The dynamic elastic modulus is evaluated using a resonance-based technique, where the response of the specimen to mechanical excitation is monitored. The measurements are performed using an accelerometer-based system (MAE C 311R device), consisting of an instrumented impact hammer, a piezoelectric sensor, and a data acquisition unit as illustrated in Fig. 1.

Figure 1. Resonance testing: a) measurement positions; b) measurement results and determination of dynamic elastic modulus; c) testing device (MAE C 311R system).

Specimens are positioned in a manner that minimises external constraints, allowing the development of natural vibration modes. The induced signal is recorded and analysed in the frequency domain using Fast Fourier Transform (FFT) from which the characteristic resonance frequencies are extracted. These frequencies, together with the measured mass and geometry of the specimens, are used to determine the dynamic modulus in accordance with relevant standardised procedures.

In order to validate the non-destructive measurements, the static modulus of elasticity is also determined experimentally. The static modulus is determined on cylindrical specimens with a diameter of 150 mm and a height of 300 mm, in accordance with EN 12390-13. The specimens are cast in steel moulds and cured in water at a temperature of 20 °C. Prior to testing, the loading surfaces are ground to ensure plane and parallel conditions. The modulus of elasticity is evaluated from the stress-strain relationship obtained during compressive loading. Longitudinal strains are measured using an extensometer with a gauge length of 90 mm. The tests are performed using a servo-controlled hydraulic testing machine with a constant loading rate of 0.6 MPa/s. To ensure stable deformation behaviour, the specimens are subjected to preloading cycles before the final measurement. The experimental setup is shown in Fig. 2.

The relationship between dynamic and static modulus is evaluated using Eq.(1):

$$k = \frac{E_s}{E_d} , \quad (1)$$

where: E_s is experimentally determined static modulus; and E_d is dynamic modulus obtained from resonance testing.

Figure 2. Measurement setup for determining the static modulus of elasticity using an extensometer.

Compressive strength is estimated from the measured or predicted static modulus using three empirical relationships. The American Concrete Institute (ACI 318) expresses the modulus of elasticity as a function of compressive strength, as given in Eq.(2), whereas the Eurocode 2 and Popovics relationships are defined by Eqs.(3) and (4), respectively. These models are originally developed for conventional concrete. All expressions are rearranged to estimate compressive strength from the corresponding static modulus values.

$$E_c = 4700\sqrt{f_c} \,, \tag{2}$$

where: E_c is static modulus of elasticity; and f_c is compressive strength.

$$E_c = 22\left(\frac{f_{cm}}{10}\right)^3 , \tag{3}$$

where: f_{cm} is mean compressive strength.

$$E_c = 3200\sqrt{f_c} + 6900 \,. \tag{4}$$

In addition to mechanical characterisation, bulk density is determined based on the measured mass and volume of specimens at different ages. The internal pore structure is analysed using an automated image analysis system (Rapid Air 457, German Instruments), in accordance with EN 480-11, as shown in Fig. 3, where the prepared sample surface and the testing device are presented.

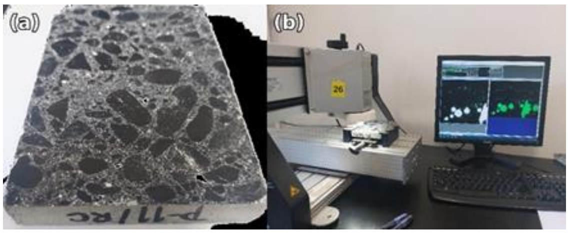

Figure 3. Air-void analysis: a) prepared sample surface for pore characterisation; b) device for air-void characterisation (Rapid Air 457 system).

The analysis is performed on polished planar sections obtained from hardened concrete specimens. Prior to measurement, the sample surface is prepared by grinding and polishing followed by surface treatment, to enhance pore visibility. The air-void system is characterised using the linear traverse method, based on the detection and counting of intersections between measurement lines and air voids. The system employs optical imaging and automated scanning along predefined paths, allowing the determination of air-void parameters such as total air content, specific surface area, and spacing factor. These parameters are used to support the interpretation of differences in bulk density, dynamic modulus, and estimated compressive strength among the investigated mixtures.

RESULTS AND DISCUSSION

The properties of specimens P1, P2, and P3 are illustrated in Fig. 4. Specimens have similar, approximately the same dimensions, confirming that the differences observed in the dynamic response are not caused by geometry. The bulk density values show that P1 has the highest density (2362.9 kg/m^3), while P2 and P3 exhibit slightly lower values (Fig. 4.). This behaviour is consistent with the modified internal structure of the mixtures, caused by air entrainment in sample P2 and the presence of low-density rubber particles in sample P3.

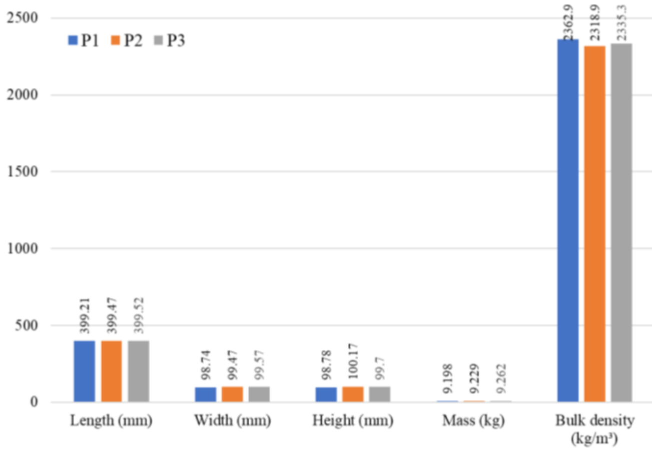

Figure 4. Average specimen properties after 803 days.

Resonance testing results presented in Fig. 5 indicate that the dynamic modulus is highest for P1, followed by P3 and P2. This confirms that the reference concrete possesses the stiffest internal structure, while the air-entrained concrete exhibits the lowest dynamic stiffness. The rubberised concrete shows intermediate behaviour, indicating that rubber particles reduce stiffness, although not as significantly as the air-void system introduced in P2.

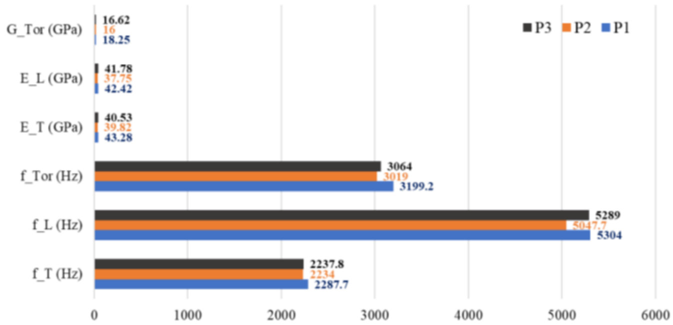

Figure 5. Average resonance frequencies and dynamic moduli after 803 days.

Measured static modulus is compared with the dynamic modulus obtained by resonance testing. Results are provided in Table 1. The ratio k ranges from 0.84 to 0.85, showing good agreement between static and dynamic measurements. The highest value is obtained for P1, whereas slightly lower values are observed for P2 and P3. These results confirm that the relationship between static and dynamic modulus is influenced by the internal structure of concrete.

Table 1. Relationship between dynamic and static modulus.

Mixture	E_d (GPa)	E_s (GPa)	$k = E_s/E_d$
P1	43.28	36.7	0.85
P2	39.82	33.9	0.85
P3	40.53	34.2	0.84

Estimated compressive strengths obtained using ACI 318, Eurocode 2, and Popovics relationships are presented in Table 2. ACI 318 and Eurocode 2 provide consistently lower strength estimates, whereas the Popovics model shows the best agreement with experimentally determined compressive strength at 90 days. This behaviour can be attributed to the fact that ACI 318 and Eurocode 2 relationships are primarily developed for structural design purposes and therefore incorporate a conservative approach to ensure an adequate level of safety in engineering practice. Consequently, these models tend to underestimate compressive strength when applied in inverse form based on measured modulus values.

Table 2. Estimated compressive strength after 803 days.

Mixture	E_d (GPa)	E_s (GPa)	k	ACI 318 (MPa)	Eurocode 2 (MPa)	Popovics (MPa)
P1	43.28	36.7	0.85	61.0	55.1	80.6
P2	39.82	33.9	0.85	52.0	42.4	66.1
P3	40.53	34.2	0.84	52.9	43.5	67.6

In contrast, the Popovics relationship provides estimates that are closer to experimentally measured values. This can be explained by the formulation of the model, which is more directly related to the mechanical behaviour of concrete and does not explicitly include design safety considerations. The good agreement also confirms the consistency between the measured static modulus and the modulus values used in the strength estimation procedure.

The RapidAir results presented in Fig. 6 show that the total air content is similar for P1 and P2, while P3 exhibits the highest air content. However, despite the similar total air content of P1 and P2, different trends are observed in the estimated strength and k ratio. This indicates that total air content alone is insufficient to explain the mechanical response of concrete. The size, distribution, and spacing of air voids also significantly influence stiffness and modulus-based strength estimation.

The comparison between experimentally measured compressive strength and NDT-based estimation is presented in Table 3. The compressive strength increases from 3 to 90 days for all investigated mixtures. The reference concrete achieves the highest compressive strength, followed by air-entrained and rubberised mixtures. When the 803-day NDT-based estimates obtained using the Popovics relationship are compared with the 90-day experimental values, the deviations are +8.3 % for P1, −6.2 % for P2, and +2.8 % for P3. These deviations can be considered acceptable for indirect long-term strength estimation.

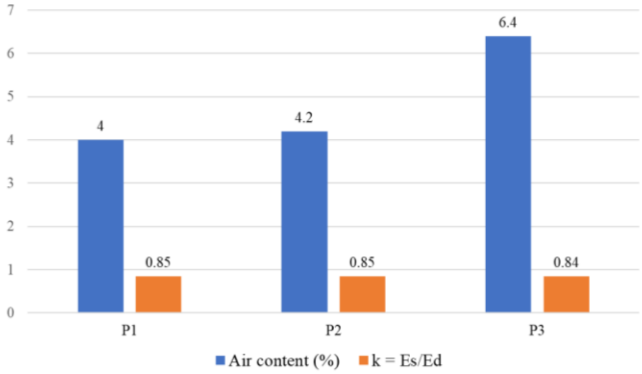

Figure 6. Air-void system and k ratio.

Table 3. Comparison between measured compressive strength and NDT-based estimation.

Mixture	3 days (MPa)	7 days (MPa)	28 days (MPa)	90 days (MPa)	NDT 803 days (MPa)	Difference 803 vs. 90 (%)
P1	47.2	59.3	70.8	74.4	80.6	+8.3
P2	43.4	50.9	63.1	70.5	66.1	−6.2
P3	41.3	47.9	56.8	65.8	67.6	+2.8

To provide a clearer comparison between the investigated empirical models, the deviations between experimentally measured compressive strength and modulus-based estimated values are summarised in Fig. 7. Results clearly show that the ACI 318 and Eurocode 2 models produce conservative estimations for all investigated mixtures. The largest deviations are observed for air-entrained concrete, indicating that the internal pore structure significantly affects modulus-based strength prediction when empirical relationships are used in inverse form.

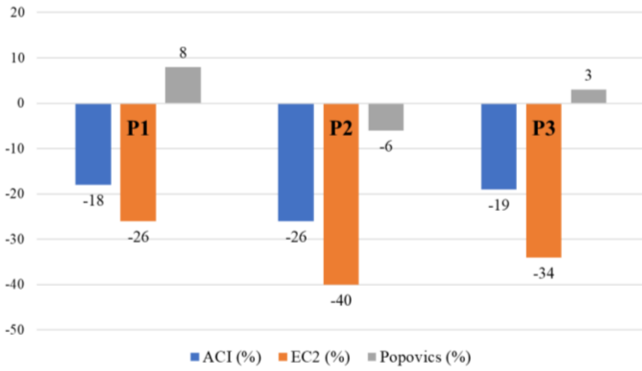

Figure 7. Deviation of estimated compressive strength.

The observed differences between investigated mixtures confirm that the accuracy of modulus-based strength estimation depends not only on the total air content, but also on the internal structure and distribution of pores. Although P1 and P2 exhibit similar total air contents, different trends are observed in the estimated strength and k ratio, suggesting that the air-void system introduced by air-entraining admixture affects the relationship between static and dynamic response. In contrast, the rubberised concrete shows relatively good agreement between measured and estimated values despite its higher air content.

The obtained results are consistent with previous studies reporting that the relationship between static and dynamic modulus depends on concrete porosity and internal heterogeneity /33-38/. Nevertheless, additional investigations on different concrete compositions and moisture conditions are necessary in order to generalise the proposed approach.

Overall, the results demonstrate that empirical relationships originally developed for conventional concrete can also be applied for long-term strength estimation of modified concretes, although their accuracy strongly depends on the internal structure of the material. Among the investigated approaches, the Popovics model provides the most reliable predictions and therefore appears to be the most suitable relationship for modulus-based non-destructive estimation of compressive strength in the investigated concretes.

CONCLUSIONS

The obtained results demonstrate that the applicability of modulus-based non-destructive strength estimation strongly depends on the internal structure of concrete. Although all investigated mixtures are produced with the same water-to-cement ratio, noticeable differences in dynamic response and estimated compressive strength are observed due to the presence of entrained air and rubber particles.

The experimentally determined ratio between static and dynamic modulus shows relatively good agreement for all investigated concretes, indicating that resonance-based testing can provide reliable long-term characterisation of concrete stiffness. However, the results also confirm that similar total air contents do not necessarily lead to similar mechanical behaviour, emphasising the importance of pore distribution and internal heterogeneity.

Among the investigated empirical relationships, ACI 318 and Eurocode 2 provide conservative estimations of compressive strength, while the Popovics relationship shows the closest agreement with experimentally measured values. The obtained deviations indicate that modulus-based non-destructive evaluation can provide realistic long-term strength estimation when an appropriate empirical relationship is applied.

Finally, the conducted investigation demonstrates that resonance-based dynamic modulus testing represents a suitable approach for long-term assessment of concrete properties, while the accuracy of strength prediction depends on the type of concrete and its internal structure.

ACKNOWLEDGEMENTS

This research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract Nos.: 451-03-33/2026-03/200012 and 200092).

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