

Non-destructive Evaluation of the Properties of Self-compacting Concrete Using Ultrasonic Testing and a Rebound Hammer

Samir Belmahi^{1,2*}, Abdelmoutalib Benfrid³, Ibrahim Klouche Djedid^{4,5}

¹ Department of Hydraulic and Civil Engineering, Institute for Science and Technology, University Centre of Maghnia, 13001 Maghnia, P.O.B. 600, Algeria

² Laboratory of Engineering and Applied Sciences, University Centre of Maghnia, 13300 Maghnia, P.O.B. 600, Algeria

³ Department of Civil Engineering, Djillali Liabes University, 22000 Sidi Bel Abbès, P.O.B. 89, Algeria

⁴ Department of Civil Engineering, University of Tiaret, Zaaroura, 14000 Tiaret, P.O.B. P 78, Algeria

⁵ Materials and Structures Laboratory (LMS), Ibn Khaldoun University of Tiaret, Zaaroura, 14000 Tiaret, P.O.B. P 78, Algeria

* Corresponding author, e-mail: s.belmahi@cu-maghnia.dz

Received: 02 April 2026, Accepted: 30 September 2026, Published online: 15 October 2026

Abstract

This study aims to improve the estimation of concrete compressive strength by combining destructive and non-destructive testing (ultrasound and sclerometer) to obtain a more precise and reliable assessment for quality control and the diagnosis of concrete structures. The experimental data were analyzed using a program linked to the Pundit Lab measurement tool to establish a regression model linking the ultrasonic propagation velocity (UPV) to the compressive strength of self-compacting concrete (SCC). SCC was formulated using a standard mix design with 450 kg/m³ of cement, 10% limestone filler (45 kg/m³), a water/cement ratio of 0.44, a gravel/sand ratio of 1.0, and a polycarboxylate-based superplasticizer. The fresh properties were evaluated using cone slump tests, L-box tests, V-funnel tests, and sieve stability tests, confirming the self-compacting nature of the mix. After 28 days of curing, five cylindrical specimens (160 × 320 mm) were subjected to ultrasonic (UPV), sclerometric, and compression tests. The results showed an average compressive strength of 39.06 MPa, a modulus of elasticity of 41.5 GPa, and a shear modulus of 16.7 GPa. The developed regression model improved the accuracy of compressive strength estimation by combining ultrasonic and sclerometric measurements, thus providing a reliable method for quality control and evaluation of existing concrete structures.

Keywords

self-compacting concrete, ultrasonic testing, rebound hammer, strength, elastic modulus

1 Introduction

Concrete is one of the most widely used construction materials because of its high compressive strength, durability, availability, and adaptability to different structural applications. Accurate determination of its mechanical properties is essential for quality control, structural design, maintenance, and assessment of existing structures. This requirement is particularly important in regions exposed to seismic activity, where inadequate concrete strength, poor construction quality, and structural deficiencies may significantly increase the vulnerability of reinforced concrete buildings. Conventional compressive testing typically requires crushing cast specimens or cores extracted from structural elements. Although these methods provide direct measurements of concrete strength, they are

time-consuming, relatively expensive, and may cause localized damage to the structure. Consequently, non-destructive testing methods are increasingly used to assess the mechanical properties, uniformity, and internal condition of concrete without significantly affecting its integrity [1]. Among these techniques, ultrasonic pulse velocity is widely used to determine the time required for compressional waves to travel through a known distance in concrete. The measured velocity is strongly influenced by the density, elastic properties, moisture content, porosity, cracking, and internal continuity of the material. Modern ultrasonic devices can record several parameters simultaneously, including transit time, calculated pulse velocity, and amplitude–time signals, thereby providing

useful information about the internal condition of concrete. However, ultrasonic pulse velocity does not directly measure compressive strength and therefore must be calibrated against destructive test results. The rebound hammer test is another rapid and practical non-destructive method used to evaluate the surface hardness of concrete. Since ultrasonic pulse velocity mainly reflects the internal continuity of the material, whereas the rebound hammer primarily characterizes surface hardness, the combined use of both methods can provide a more reliable assessment than either technique used separately [2].

Adding tiny particles to concrete and using predictive homogenization models to improve it have been the subjects of extensive research. Non-destructive testing has been widely used to assess the mechanical properties and overall condition of concrete structures without causing significant damage. Breyse [1] discussed the reliability and limitations of both individual and combined testing techniques, showing that the use of complementary methods can improve the accuracy of structural assessment [1, 3]. Bungey et al. [2] provided practical guidance on the selection, application, calibration, and interpretation of *in situ* concrete testing methods [2, 3]. Malhotra and Carino [3] reviewed a broad range of non-destructive and partially destructive techniques for evaluating concrete strength, durability, and internal defects, emphasizing the importance of proper calibration and combined testing approaches for obtaining more reliable results.

A growing number of studies have examined the use of nanoscale additives and micromechanical models to improve the performance of cement-based composites. Chatbi et al. [4] showed that incorporating nano-silica can enhance the strength and deformability of concrete slabs, and that the modified Voigt model successfully predicted their effective mechanical properties. In later work, Chatbi et al. [5] investigated silica-rich nano-clay and reported further improvements in the strength and durability of cementitious materials. A broader review also emphasized the role of nano-clay in refining the internal structure of concrete and improving its long-term behavior [6]. In a related study, Sid Ahmed et al. [7] investigated sustainable composites containing recycled PET and highlighted their potential as environmentally friendly materials. In a subsequent study, Sid Ahmed et al. [8] examined mortars incorporating plastic waste and found good agreement between the experimental results and the Hashin–Shtrikman bounds. Belmahi et al. [9] studied the effect of chemical exposure on cementitious materials and showed that alkaline conditions can

significantly reduce the mechanical properties of concrete and mortar. Likewise, these studies demonstrate the potential of nanoparticle reinforcement and micromechanical modeling for developing stronger, more durable, and more sustainable cementitious composites, including self-compacting concrete.

Recent studies show that ultrasonic methods are good at finding structural problems. According to Brougui et al. [10], the speed of ultrasonic waves is a good indicator of the severity of a crack in a wooden structure. This facilitates the performance of a reliable structural assessment. Navarrete-Seras et al. [11] developed an extensive methodology that combines ultrasonic measurements with finite element modeling to assess rock quality. This method was closely related to how the rock's shape changes. Pons et al. [12] investigated hybrid fiber-reinforced self-compacting concrete and reported an improved mechanical response under bending. They also observed stronger fiber–matrix bonding than in comparable vibrated concrete. Dufka et al. [13] investigated crystalline admixtures using both chemical and ultrasonic methodologies. They found that chemical resistance improved without compromising mechanical performance. Nosratzahi and Miri [14] investigated chloride infiltration into self-compacting concrete (SCC) and demonstrated its enhanced durability in marine environments compared with traditional concrete.

Subsequent studies examined the properties of self-compacting concrete (SCC). Ponikiewski and Katzer [15] found that the type and amount of fiber have a big effect on how fresh SCC looks and works. Ivanchev and Slavchev [16] likewise demonstrated that ultrasonic pulse velocity can be used to assess cracks and damage in reinforced concrete structures. Işık et al. [17] demonstrate that unplanned vertical extensions substantially increase shear demand and diminish the seismic performance of reinforced concrete buildings, thereby increasing structural vulnerability. Işık et al. [17] show that FRP retrofitting, along with improved materials such as self-compacting concrete (SCC) and ultrasonic testing, can restore shear capacity and make buildings safer during earthquakes. Salhi et al. [18] investigated SCC in settings marked by high temperatures and strong chemicals. They found that workability decreased and degradation increased over time. Işık et al. [19] demonstrate that the Kahramanmaraş earthquakes caused significant damage to reinforced concrete buildings due to structural anomalies, including soft stories and inadequate design practices. Işık et al. [19] point out that using self-compacting concrete (SCC) and ultrasonic testing can improve construction and allow for

effective non-destructive structural assessment. Işık [20] point out that the major damage observed in RC structures after earthquakes is primarily due to insufficient shear reinforcement and weak concrete, which result in poor performance in earthquakes. Işık [20] show that using steel and aramid fibers to strengthen structures, possibly with self-compacting concrete (SCC) and ultrasonic testing, can greatly improve shear capacity and structural reliability. Adding fly ash to SCC can improve several performance indicators, although excessive replacement may reduce compressive strength, as reported by Khatib [21]. Iqbal et al. [22] found that the optimal amount of fly ash for lightweight SCC made it easier to work with and stronger. Karatas and Gunes [23] studied fiber-reinforced SCC and found that the right amount of fiber improves both the fresh and hardened properties. Karahan et al. [24] compared conventional compressive strength tests with ultrasonic pulse velocity and rebound hammer measurements, showing that both individual and combined non-destructive techniques can provide reliable estimates of concrete strength. Xiao et al. [25] later proposed an image-based approach using convolutional neural networks to evaluate the quality of self-compacting concrete. Among the models considered, Res-Net18 delivered the best results, achieving an (R^2) value of 0.9987 and demonstrating the potential of image recognition as a rapid, affordable, and non-destructive inspection method [25]. Consiglio et al. [26] investigated prestress losses in concrete beams by comparing a modified saw-cut technique with a destructive cracking method. Consiglio et al. [26] showed that strain-based measurements can provide dependable information on the residual prestress level of concrete members. Taken together, the reviewed studies demonstrate the importance of combining conventional mechanical tests with non-destructive and data-driven techniques to improve the evaluation of concrete structures. Nevertheless, the accuracy of non-destructive correlations depends on several parameters, including concrete composition, aggregate characteristics, curing conditions, moisture content, testing age, equipment type, and the number of specimens used for calibration. Consequently, prediction models developed for a specific concrete mixture cannot be generalized without additional calibration and validation. The overall experimental program involved incorporating limestone filler at substitution rates of 10%, 20%, and 30%. However, this article focuses exclusively on the 10% dosage, selected from the entire experimental campaign to provide a detailed analysis of its behavior in both the fresh and hardened states. This choice was motivated by

the desire to limit the scope of the study and present an in-depth analysis of the performance of this formulation, while the results obtained for the other dosages of 20% and 30% will be the subject of a future separate publication. The work comprises several steps: the preparation of the mixture and its characterization in the fresh state through spread, L-box, V-funnel, and sieving tests; the preparation of five 160 mm × 320 mm cylinders; Direct measurements of ultrasonic propagation velocity (UPV) and rebound Hammer were performed, followed by a destructive compression test and finally the calculation of dynamic elastic parameters. The originality of this study lies in the combination of destructive and non-destructive testing techniques (Rebound Hammer-ultrasound) applied to self-compacting concrete with limestone aggregate. The experimental results were analyzed using a data analysis system (Data) to establish correlations between the measured parameters and improve the accuracy of the compressive strength estimation. This approach offers a more reliable evaluation method for quality control and the diagnosis of existing concrete structures.

2 Ultrasonic testing

2.1 Density of concrete (ρ) by ultrasonic testing

To determine the dynamic modulus of elasticity by ultrasonic testing, it is necessary to know the density of the concrete. This parameter is obtained from cast or cored samples. Fig. 1 shows a study of how concrete density changes with ultrasonic wave velocity measured in cores drilled from 13 bridges. The following relationship was established [27]:

$$\rho = 1.67 + 0.155 V, \quad (1)$$

where:

- ρ is the concrete density (kg/m^3);
- V is the ultrasonic wave velocity (km/s).

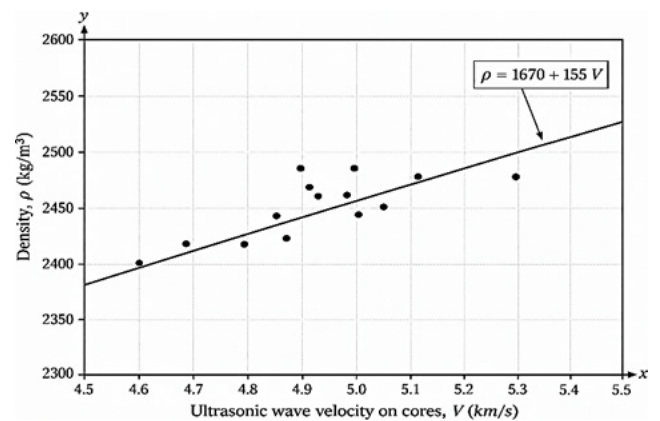


Fig. 1 Concrete density as a function of ultrasonic wave velocity measured on core samples

This method does not require samples; it is sufficient to measure the propagation speed of ultrasonic waves *in situ*. The author states that this relationship is valid only for speeds between 4.5 and 5.5 km/s, as illustrated in Fig. 1.

2.2 Dynamic Young's modulus (E) by ultrasonic testing

This is Hooke's law. So, Young's modulus is the slope of the first linear part of the stress-strain curve. When tensile loading happens, the material stretches in the direction of the stress (normal strain ε_n) and shrinks in the opposite direction (transverse strain ε_t). Poisson's ratio describes how these two opposite deformations are related [28]:

$$\sigma = E \times \varepsilon. \quad (2)$$

This is Hooke's law. So, Young's modulus is the slope of the first linear part of the stress-strain curve. When tensile loading happens, the material stretches in the direction of the stress (normal strain ε_n) and shrinks in the opposite direction (transverse strain ε_t). Poisson's ratio describes how these two opposite deformations are related [29]:

$$\nu = -\frac{\varepsilon_t}{\varepsilon_n}. \quad (3)$$

When a mechanical vibration travels through a material, it causes the material to bend elastically (it returns to its original shape after the wave has passed). In this case, Young's modulus (E) and Poisson's ratio ν are related to the velocity of the longitudinal wave V_L . To find the dynamic Young's modulus (E_d) of concrete can be determined using Eq. (4) with the ultrasonic pulse velocity and Poisson's ratio:

$$E_d = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \rho V_L^2, \quad (4)$$

where:

- E is the dynamic Young's modulus (modulus of elasticity) of concrete (MPa);
- γ is the concrete density (kg/m^3);
- V is the ultrasonic wave velocity (m/s).

As a function of ν (Poisson's ratio), this relationship can be written as an equation [30]:

$$E = \rho \times f'(\nu) \times V_L^2, \quad (5)$$

when:

$$f'(\nu) = \frac{(1+\nu) \times (1-2\nu)}{(1-\nu)}. \quad (6)$$

Poisson's ratio ν can be determined in the laboratory using either a destructive or non-destructive method. In de-

structive tests, the ratio between the transverse and longitudinal strain of a sample allows for the measurement of strain in samples of known dimensions. In non-destructive testing, ultrasonic measurements can be used to assess a specimen or a structural element directly. This is done by using the transverse pulse velocity V_T and the longitudinal pulse velocity V_L .

$$\nu = \frac{(V_L^2 - 2V_T^2)}{2(V_L^2 - V_T^2)} \quad (7)$$

The value of Poisson's ratio for concrete usually falls between 0.20 and 0.35, with an average value of about 0.24. This depends on the quality of the concrete. The values of this modulus vary from 20 to 50 MPa; they depend on the quality of the concrete. For this case, the modulus of elasticity can be written like this [31]:

$$E = \rho \times V_T^2 \frac{(3V_L^2 - 4V_T^2)}{(V_L^2 - V_T^2)}. \quad (8)$$

2.3 Shear modulus (G) by ultrasonic testing

Shear waves, or S-waves, propagate on the surface of concrete at a velocity V_T , which can be expressed as a function of the shear modulus G , generally between 8.3 and 20.8 GPa, corresponding to a modulus of elasticity of concrete between 20 and 50 GPa [32]:

$$V_T = \sqrt{\frac{G}{\rho}}, \quad (9)$$

where:

$$G = \rho \times V_T^2. \quad (10)$$

2.4 Bulk modulus (K) by ultrasonic testing

Equation (11) [32] is used to calculate the dynamic bulk modulus (K) from the longitudinal wave velocity (V), transverse wave velocity (V_t), and material density (ρ):

$$K = \rho \frac{(V_L^2 - 4V_T^2)}{3}. \quad (11)$$

2.5 Lamé's constant (λ) by ultrasonic testing

Lamé's first parameter (λ) can be determined from the longitudinal wave velocity (V), transverse wave velocity (V_t), and material density (ρ), using Eq. (12) [32]:

$$\lambda = \rho (V_L^2 - 2V_T^2). \quad (12)$$

The elastic constants above are set up so that they are always positive. Shear modulus G tells, how well the

material can handle shear stress. Liquids do not withstand shear stress; consequently, $\mu = G = 0$ and the Poisson's ratio $\nu = 0.5$ [33, 34].

2.6 Estimation of strength (R) by ultrasonic testing

Tensile testing is a common way to find out how strong metals are. But tensile tests are difficult to perform and are not usually useful for non-metallic materials like concrete and ceramics. In these instances, measuring the velocity of ultrasonic pulses is a well-known, widely used non-destructive method for estimating material strength [35]. The compressive strength (R) of concrete is represented by the combined method (ultrasound-rebound hammer) as a multiple correlation function derived from the equation of a hyperboloid's area. Based on Jones' results, the lower limit for good-quality concrete is between 4.1 and 4.7 (km/s):

$$R = a \times V^b \times S^c, \quad (13)$$

where:

- V is the ultrasonic pulse velocity (m/s).
- S is the rebound value obtained from the rebound hammer.
- a , b , and c are the coefficients of the regression equation, determined using the least squares method.

This approach is based on the Laplace–Gauss normal distribution model, and in some cases, the Pearson distribution [36]. In this study, the Pundit-Lab ultrasonic device was used, based on this principle, to estimate the material's mechanical strength. Table 1 presents the conditions of concrete structures as a function of ultrasonic velocity.

3 Experimental procedure

3.1 Mix design of the studied concretes

The concrete mixtures were prepared using locally sourced materials from Algeria. The cement used was Portland-limestone cement (CEM II/A-L 42.5), in accordance with the technical specifications provided by the Groupe Industriel des Ciments d'Algérie (GICA) [37], made by the Mascara cement plant in Algeria and certified by both the

Algerian standard NA 442:2013 [38] and the European standard EN 197-1:2011 [39]. The National Aggregates Company (ENG) in Tlemcen [40] provided the limestone filler, made from dolomitic limestone [41]. MEDAFLOW 3041R, a high-range water-reducing admixture (superplasticizer) made by GRANITEX (Algeria) from synthetic polymers [42], was used. The water used to mix was just regular tap water. The fine aggregate was natural sand, ranging in size from 0 to 4 mm, with a fineness modulus of 2.2. The coarse aggregate was 8/16 mm crushed gravel that could absorb no more than 2% water. The Guelta and Kbobba quarries in the Tiaret region provided these aggregates [43]. The mix was made with the following specifications: 450 kg/m³ of cement, a gravel-to-sand ratio (G/S) of 1, a water-to-cement ratio (w/c) of 0.44, and 10% limestone filler. The final composition has been summarized in Table 2. This self-compacting concrete (SCC) is different from regular concrete in that it has different properties when it is fresh and can mold, embed, and compact just by the force of gravity. Figs. 2 to 6 represent the different tests recommended by the French Association of Civil Engineering (FAGC) to verify the quality of self-compacting concrete. The results of these tests are summarized in Table 3. Regarding the hardened

Table 2 Composition of the self-consolidating concrete (SCC) examined

Component	Value
Cement, C (kg/m ³)	450
Coarse aggregate, 8/16 mm (kg/m ³)	870
Natural sand, 0/4 mm (kg/m ³)	870
Water, W (L/m ³)	200
Superplasticizer (L/m ³)	6.5
Limestone filler (kg/m ³)	45
w/c	0.44
G/S	1.00
$W/(C + \text{limestone filler})$	0.40



Fig. 2 Sieve-stability in the self-compacting concrete

Table 1 Condition of concrete structures as a function of ultrasonic velocity [35, 36]

Velocity (m/s)	Qualitative condition
≥ 4575	Excellent
3600–4574	Good
3050–3599	Questionable
2135–3049	Poor
< 2135	Very poor



Fig. 3 Concrete mixing in the self-compacting concrete



Fig. 4 V-funnel test in the self-compacting concrete



Fig. 5 Self-compacting concrete sprawl test

state tests, 16×32 cm specimens were filled with concrete, demolded after 24 h, and cured in water at 20°C for 28 days according to Kedjour [44]. Subsequently, destructive and non-destructive tests were carried out.

The findings are consistent with the FAGC recommendations, indicating that the concrete is self-compacting.



Fig. 6 L-box test in the self-compacting concrete

Table 3 The quality of the self-compacting concrete made

Test	Measured value	Acceptance criterion	Class / interpretation
Slump flow	685 mm	660–750 mm	SF2
L-box passing ratio	0.86	≥ 0.80	Passing ability satisfied
Sieve segregation	12%	0–15%	Stable / SR1
V-funnel time	20 s	< 25 s	VF2

4 Results and discussion

The Pundit Lab software (Proceq SA, Schwerzenbach, Switzerland) [45] was used to analyze the experimental data and establish the regression model linking the ultrasonic propagation velocity (UPV) to the compressive strength of self-compacting concrete (SCC). This software calculates the regression coefficients required for the prediction model and allows for the direct estimation of compressive strength from the measured ultrasonic propagation velocity (Table 4) and the properties of SCC (Table 5). Figs. 7 to 11 present examples of ultrasonic waveforms, illustrating the determination of the times of first arrival (t_1 and t_2), waveform analysis, and identification of maximum amplitudes. These signal processing results enable the precise determination of the ultrasonic wave transit time and facilitate the evaluation of the dynamic mechanical properties of the concrete, thus ensuring the reliability, consistency, and reproducibility of the experimental measurements. In Table 4, F_{ck} represents the compressive strength obtained from a destructive test by a universal compression machine, R represents the compressive strength from a combined non-destructive test (ultrasound-sclerometer).

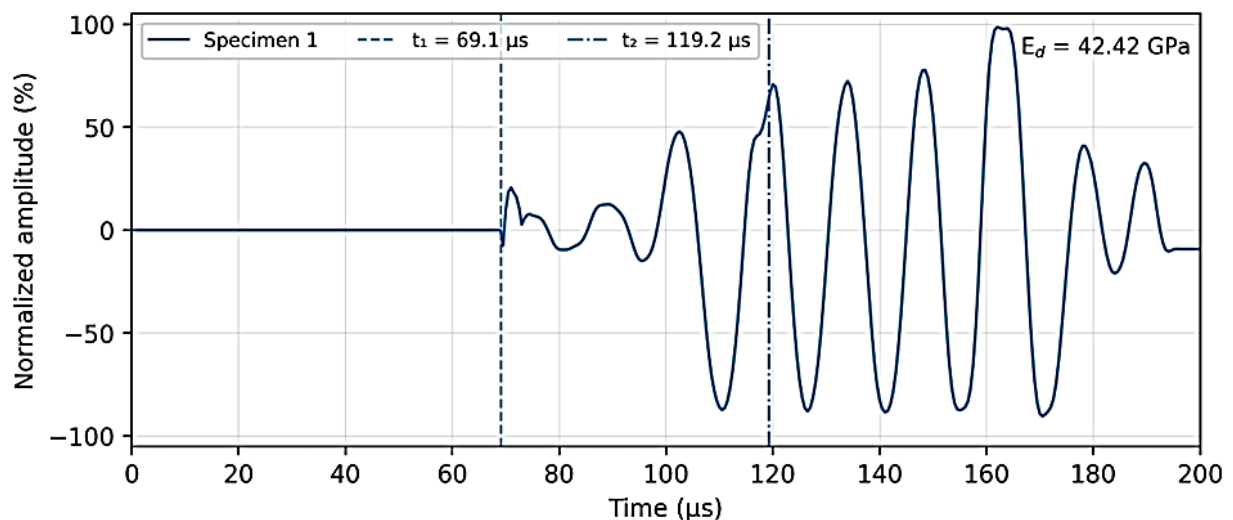
To establish a reliable SONREB correlation for predicting the compressive strength of self-compacting concrete (SCC), ultrasonic pulse velocity (UPV) and Schmidt hammer rebound measurements were performed on all specimens and correlated with the compressive strengths obtained from destructive compression tests. As reported in previous

Table 4 Measurement results on specimens (160 mm × 320 mm)

Sample No.	1	2	3	4	5	Average
Compressive strength (with compression machine) F_{ck} (MPa)	40.10	38.50	40.30	37.80	38.60	39.06
Ultrasonic pulse velocity (V_L) m/s	4632	4438	4644	4426	4611	4550.2
Rebound number (S)	45	42	46	38	43	42.8
Constant (exponential curve)	$a = 3.0123$; $b = 0.000549$; $R = 0.8721$ (R -square)					/
Compressive strength: $R = f_c = a \times V_b \times S_c$	39.70	38.30	40.30	37.80	39.20	39.06
Constants	$a = 6.52485E-05$; $b = 1.50085173$; $c = 0.16546280$; $R^2 = 0.918975531$ (R -square)					/

Table 5 The measured and calculated characteristics of the self-compacting concrete

Property	Density basis	1	2	3	4	5	Average
Compressive strength (MPa)		40.10	38.50	40.30	37.80	38.60	39.06
Length, L (m)		0.320	0.320	0.320	0.320	0.320	0.320
Diameter (m)		0.160	0.160	0.160	0.160	0.160	0.160
Mass, m (kg)		15.10	14.90	15.10	14.90	15.00	15.00
Volume (m^3)		0.0064	0.0064	0.0064	0.0064	0.0064	0.0064
Longitudinal time, t_1 (μs)		69.10	72.10	68.90	72.30	69.40	70.36
Transverse time, t_2 (μs)		119.20	123.00	119.20	122.60	119.60	120.72
Longitudinal velocity, V_L (m/s)		4632	4438	4644	4426	4611	4550.20
Transverse velocity, V_T (m/s)		2685	2602	2685	2610	2676	2651.60
Measured density, ρ_1 (kg/ m^3)		2359.38	2328.13	2359.38	2328.13	2343.75	2343.75
Estimated density, ρ (kg/ m^3)		2387.96	2357.89	2389.82	2356.03	2384.71	2375.28
Dynamic Young's modulus, E^d (GPa)	with ρ_1	42.42	39.03	42.49	39.12	41.83	40.98
	with ρ	42.93	39.53	43.04	39.59	42.56	41.53
Poisson's ratio, ν		0.250	0.240	0.250	0.230	0.250	0.244
Dynamic shear modulus, G^d (GPa)	with ρ_1	17.01	15.76	17.01	15.86	16.78	16.48
	with ρ	17.22	15.96	17.23	16.05	17.08	16.71
Dynamic bulk modulus, K (GPa)	with ρ_1	27.94	24.84	28.21	24.46	27.45	26.58
	with ρ	28.28	25.16	28.57	24.75	27.93	26.94
Lamé's first parameter, λ (GPa)	with ρ_1	16.60	14.33	16.87	13.89	16.26	15.59
	with ρ	16.80	14.51	17.08	14.05	16.55	15.80


Fig. 7 Ultrasonic signal of self-compacting concrete – determination of arrival times and dynamic modulus ($t_1 = 69.1 \mu s$; $t_2 = 119.2 \mu s$; $R = 42420.78$ MPa)

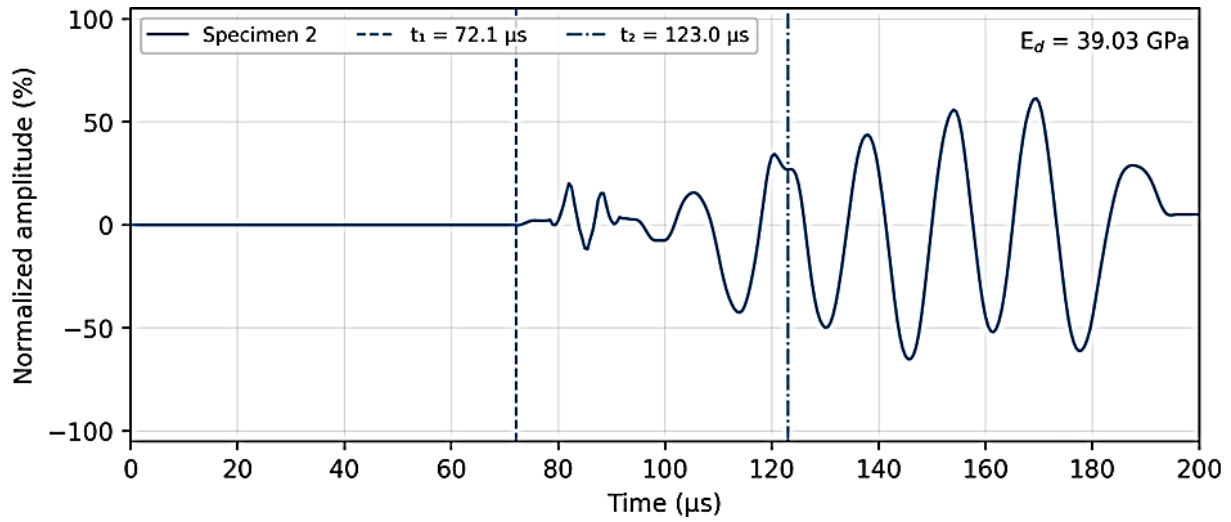


Fig. 8 Ultrasonic signal of self-compacting concrete – wave propagation analysis and dynamic modulus evaluation ($t_1 = 72.1 \mu s$; $t_2 = 123.0 \mu s$; $R = 39028.56 \text{ MPa}$)

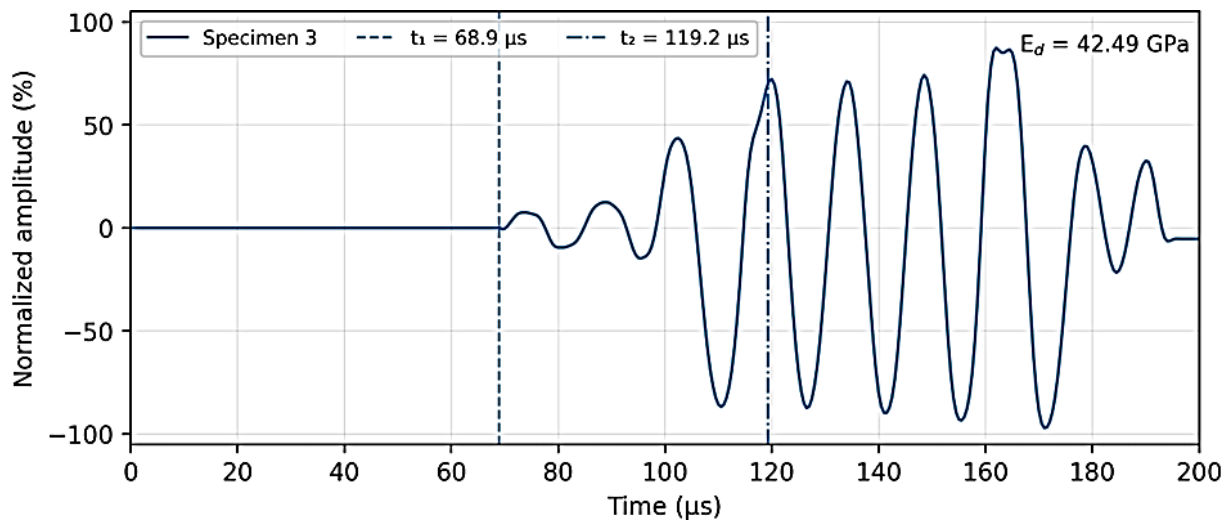


Fig. 9 Ultrasonic signal of self-compacting concrete – transit time measurement and amplitude response ($t_1 = 68.9 \mu s$; $t_2 = 119.2 \mu s$; $R = 42487.52 \text{ MPa}$)

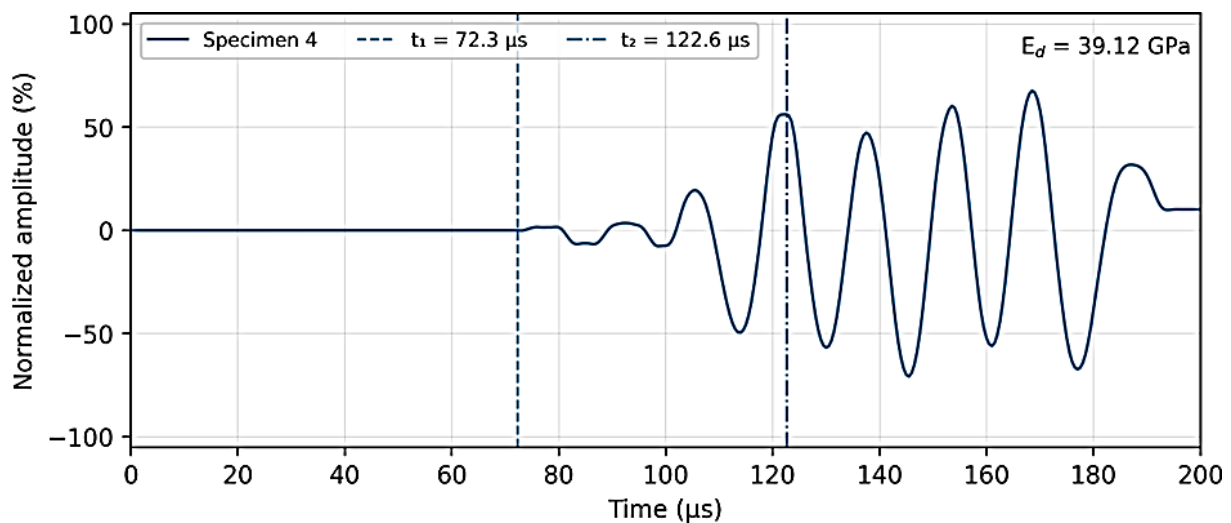


Fig. 10 Ultrasonic signal of self-compacting concrete – signal analysis and dynamic parameter determination ($t_1 = 72.3 \mu s$; $t_2 = 122.6 \mu s$; $R = 39123.09 \text{ MPa}$)

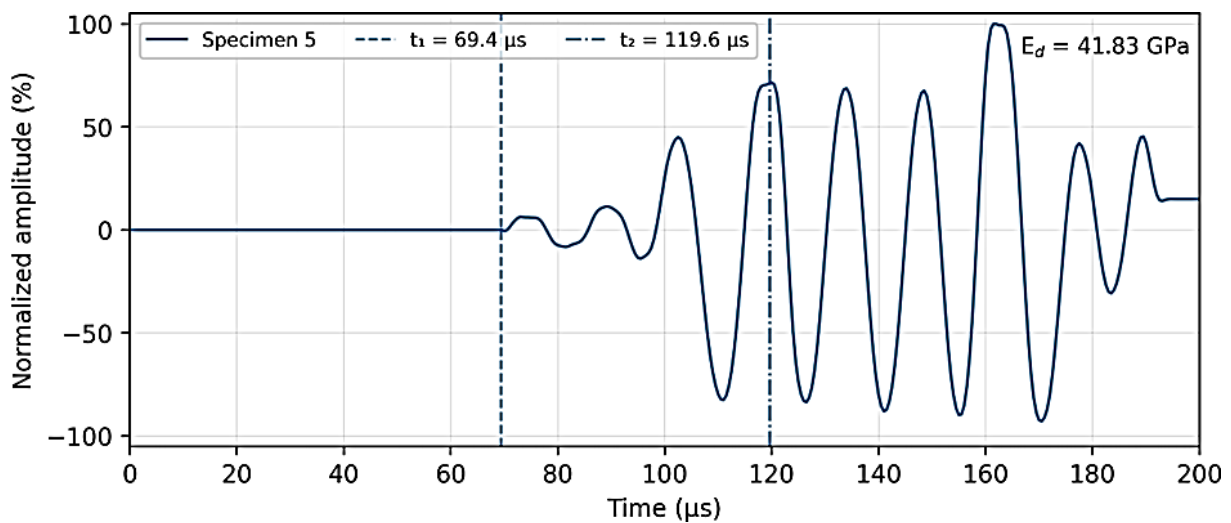


Fig. 11 Ultrasonic signal of self-compacting concrete – final signal response and mechanical property evaluation ($t_1 = 69.4 \mu\text{s}$; $t_2 = 119.6 \mu\text{s}$; $R = 41826.96 \text{ MPa}$)

studies, combining complementary non-destructive techniques generally provides a more reliable estimation of concrete strength than either method used independently [1–3]. The experimental results (Tables 4 and 5) demonstrate good reproducibility of the SCC mixtures. The compressive strength varied only slightly, from 37.8 to 40.3 MPa, indicating a uniform mechanical response. Likewise, UPV values ranged from 4,426 to 4,644 m/s, which is typical of dense and well-compacted concrete. Rebound hammer values also exhibited limited variation, reflecting minor differences in surface condition, aggregate distribution, and moisture content. A clear positive relationship was observed between UPV and compressive strength, with a coefficient of determination of $R^2 = 0.8721$, confirming that ultrasonic velocity is a reliable indicator of the mechanical quality of SCC. When the UPV and rebound hammer results were combined using the SONREB approach, the correlation improved to approximately $R^2 = 0.92$. This improvement highlights the complementary nature of the two techniques: UPV primarily reflects the internal density and continuity of the concrete, whereas the rebound index is mainly influenced by surface hardness. The resulting correlation agrees well with previous investigations reporting that combined UPV–rebound relationships generally provide more accurate strength predictions than individual non-destructive methods [1–3]. The high coefficient of determination therefore supports the applicability of the proposed SONREB model for the investigated SCC. The relationship between UPV and compressive strength is associated with the progressive densification of the cementitious matrix during hydration. As hydration proceeds, pore volume decreases and the internal microstructure become more continuous, allowing ultrasonic waves to propagate more rapidly while simultaneously

increasing concrete stiffness and compressive strength. Consequently, higher UPV values are generally associated with improved mechanical performance [1–3]. The physical and dynamic elastic properties summarized in Table 5 further confirm the quality and homogeneity of the concrete. The measured densities fall within the expected range for normal SCC, indicating adequate consolidation and the absence of significant internal defects. Only minor variations were observed in longitudinal and shear-wave transit times, suggesting limited differences in internal compactness. Correspondingly, the calculated dynamic Young's modulus ranged from approximately 39 to 43 GPa, demonstrating high stiffness consistent with the measured compressive strengths. Similar behavior was observed for the shear modulus and Lamé's constant, whereas Poisson's ratio remained nearly constant, indicating comparable deformation characteristics among all specimens. The narrow ranges of density, wave velocity, compressive strength, and dynamic elastic parameters demonstrate satisfactory experimental repeatability and overall material homogeneity. The ultrasonic waveforms presented in Figs. 7–11 support these observations. Specimens exhibiting shorter transit times showed higher ultrasonic velocities and dynamic Young's moduli approaching 42–43 GPa, indicating dense and well-compacted microstructures. In contrast, slightly longer transit times were associated with lower dynamic moduli (approximately 39 GPa), suggesting the presence of limited internal heterogeneity or localized porosity. Overall, the waveforms confirm the good structural continuity of the investigated concrete, with only minor specimen-to-specimen variations that are typical of laboratory-produced SCC. From an engineering perspective, the proposed SONREB correlation provides a practical and non-destructive means of estimating

the compressive strength of SCC without extracting cores or damaging structural elements. Such an approach is particularly useful for construction quality control and for the evaluation of existing structures where destructive testing is impractical or undesirable [1–3]. Nevertheless, it should be emphasized that SONREB relationships are influenced by mixture composition, aggregate characteristics, curing conditions, concrete age, and moisture content. Consequently, the proposed equation should be applied primarily to concretes with characteristics similar to those investigated in the present study. Additional validation using different SCC mixtures, ages, and environmental conditions would further improve the robustness and general applicability of the model. Overall, the investigated self-compacting concrete exhibited satisfactory and high compressive strength.

5 Conclusions

This study demonstrated that incorporating 45 kg/m³ of limestone filler (10% of the cement mass) enabled the production of a self-compacting concrete satisfying the main fresh-state requirements, including adequate filling ability, passing ability, and resistance to segregation. At 28 days, the concrete achieved an average compressive strength of 39.06 MPa and exhibited ultrasonic pulse velocity values indicative of a dense and relatively homogeneous internal structure. The calculated dynamic elastic parameters were consistent with those expected for normal-strength self-compacting concrete. The non-destructive evaluation showed that UPV and SONREB techniques are useful for comparative quality assessment. However, the moderate correlations obtained ($R^2 \approx 0.69$) indicate that the proposed relationships are valid only for the investigated mixture and experimental conditions and should not be considered as general predictive models for SCC compressive strength. Further studies involving a larger number of specimens, wider strength ranges, and different mixture compositions are required to establish robust and broadly applicable non-destructive prediction models.

6 Index

Fig. 12 [46] shows a common signal that is used to set transmission timings and signal amplitudes. In this conversation:

- A_p is the amplitude of the longitudinal wave;
- A_{ps} is the amplitude of the transverse (shear) wave;
- $t_p = t_1$ is the transmission time of the longitudinal wave;
- $t_s = t_2$ is the transmission time of the torsional (shear) wave.

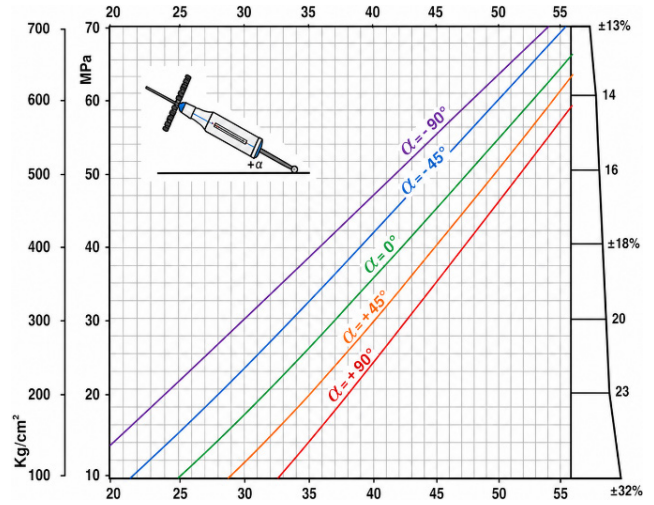


Fig. 12 A typical diagram illustrating the transmission time and node amplitude [46]

Longitudinal wave, which is the first type of wave to move through the medium as it spreads. The parameter t_p (or t_1) shows the moment when the longitudinal wave first reaches a certain point. This is the time it takes for the wave to travel. After the first wave, the second type of wave that forms are called a transverse or shear wave. People also call it the shear wave. The A_{ps} represents amplitude, and it usually arrives later because it moves more slowly. The shear (or torsional) wave is recognized at the exact moment that corresponds to the transmission time t_s (or t_2), which is the time that is important for this wave to travel. The main goal of this graphic is to help people tell the difference between the two wave modes, which are shear and longitudinal. It does this by showing the wave amplitudes and the times at which each mode arrives [2].

Fig. 13 [44] illustrates the relationship between the rebound number measured using a Schmidt rebound hammer and the estimated compressive strength of concrete. The horizontal axis represents the rebound number, while the vertical axis gives the corresponding compressive strength in MPa and kg/cm². Separate conversion lines are provided

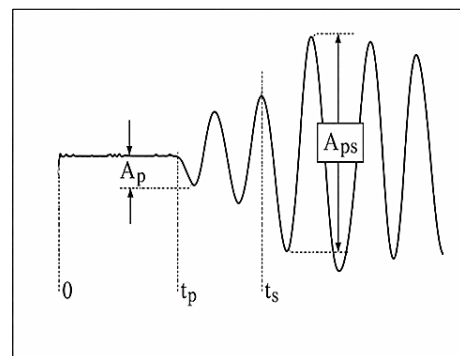


Fig. 13 Conversion curve relating the rebound number to the compressive strength of concrete for different rebound hammer impact angles [44]

for different impact angles, ranging from -90° to $+90^\circ$, because the orientation of the hammer affects the rebound value due to gravitational effects on the internal mass. The appropriate line must therefore be selected according to the testing direction. In general, a higher rebound number indicates a higher estimated compressive strength. However,

the values obtained from this chart should be considered approximate, since rebound measurements may also be influenced by surface condition, moisture content, carbonation, aggregate type, and concrete age. Whenever possible, the results should be verified using core tests or a project-specific calibration curve [44, 46].

References

- [1] Breysse, D. "Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods", *Construction and Building Materials*, 33, pp. 139–163, 2012. <https://doi.org/10.1016/j.conbuildmat.2011.12.103>
- [2] Bungey, J. H., Millard, S. G., Grantham, M. G. "Testing of Concrete in Structures", CRC Press, 2006. ISBN 9780429190957
- [3] Malhotra, V. M., Carino, N. J. (eds.) "Handbook on Nondestructive Testing of Concrete", CRC Press, 2004. ISBN 0849314852
- [4] Chatbi, M., Krour, B., Benatta, M. A., Harrat, Z. R., Amziane, S., Bouiadjra, M. B. "Bending analysis of nano-SiO₂ reinforced concrete slabs resting on elastic foundation", *Structural Engineering and Mechanics*, 84(5), pp. 685–697, 2022. <https://doi.org/10.12989/sem.2022.84.5.685>
- [5] Chatbi, M., Harrat, Z. R., Benatta, M. A., Krour, B., Hadzima-Nyarko, M., Işık, E., Czarnecki, S., Bouiadjra, M. B. "Nano-Clay Platelet Integration for Enhanced Bending Performance of Concrete Beams Resting on Elastic Foundation: An Analytical Investigation", *Materials*, 16(14), 5040, 2023. <https://doi.org/10.3390/ma16145040>
- [6] Niu, X.-J., Li, Q.-B., Hu, Y., Tan, Y.-S., Liu, C.-F. "Properties of cement-based materials incorporating nano-clay and calcined nano-clay: A review", *Construction and Building Materials*, 284, 122820, 2021. <https://doi.org/10.1016/j.conbuildmat.2021.122820>
- [7] Sid Ahmed, M., Hacini, M., Benosman, A. S., Taleb, O., Benachenhou, K. A., Benfrid, A., Hachemi, H., Mouli, M., Badache, A. "Development of Eco-Friendly Composite Mortars for the Circular Economy and Sustainable Construction: Rheological, Thermo-Mechanical, Durability Characterization, and Environmental Impact Assessment (LCA)", *Circular Economy and Sustainability*, 6(2), 80, 2026. <https://doi.org/10.1007/s43615-026-00747-z>
- [8] Sid Ahmed, M., Benfrid, A., Benosman, A. S., Hacini, M., Mouli, M., Taleb, O., Badache, A. "Analysis of thermally treated "plastic-pozzolanic" modified mortars and their mechanical properties", *Zastita Materijala*, 67(3), pp. 479–490, 2026. <https://doi.org/10.62638/ZasMat1595>
- [9] Belmahi, S., Benfrid, A., Klouche Djedid, I., Guergour, R., Djakhane, N. "Influence of Acidic and Alkaline Environments on the Mechanical Properties of Cement Mortars", *Periodica Polytechnica Civil Engineering*, 70(1), pp. 315–326, 2026. <https://doi.org/10.3311/PPci.42312>
- [10] Brougui, M., Andor, K., Szabó, P. "Assessment of Defect Severity in Wooden Pillars Using Ultrasonic Testing", *Periodica Polytechnica Civil Engineering*, 69(3), pp. 966–975, 2025. <https://doi.org/10.3311/PPci.40197>
- [11] Navarrete-Seras, M. A., Alonso-Guzmán, E. M., Martínez-Molina, W., Chávez-García, H. L., Arreola-Sánchez, M., Borrego-Perez, J. A., Cervantes-Servín, A. I. "Finite Element Modeling with Ultrasonic Pulse Velocity for Visualising Rock Deformations", *Periodica Polytechnica Civil Engineering*, 69(2), pp. 470–481, 2025. <https://doi.org/10.3311/PPci.38644>
- [12] Pons, G., Mouret, M., Alcantara, M., Granju, J. L. "Mechanical behaviour of self-compacting concrete with hybrid fibre reinforcement", *Materials and Structures*, 40(2), pp. 201–210, 2007. <https://doi.org/10.1617/s11527-006-9131-y>
- [13] Dufka, Á., Žižková, N., Brožovský, J. "An Analysis of Crystalline Admixtures in Terms of Their Influence on the Resistance of Cementitious Composites to Aggressive Environments", *Periodica Polytechnica Civil Engineering*, 65(1), pp. 344–352, 2021. <https://doi.org/10.3311/PPci.14514>
- [14] Nosratzahi, N., Miri, M. "Experimental Investigation on Chloride Diffusion Coefficient of Self-Compacting Concrete in the Oman Sea", *Periodica Polytechnica Civil Engineering*, 64(3), pp. 647–657, 2020. <https://doi.org/10.3311/PPci.15335>
- [15] Ponikiewski, T., Katzer, J. "Fresh Mix Characteristics of Self-Compacting Concrete Reinforced by Fibre", *Periodica Polytechnica Civil Engineering*, 61(2), pp. 226–231, 2017. <https://doi.org/10.3311/PPci.9008>
- [16] Ivanchev, I., Slavchev, V. "About the Possible Limitations in the Usage of the Non-Destructive Ultrasonic Pulse Velocity Method for Assessment of Cracks in Reinforced Concrete Structures, Subjected to Direct Environmental Exposure", *Buildings*, 9(9), 202, 2019. <https://doi.org/10.3390/buildings9090202>
- [17] Işık, E., Shao, Y.-B., Hadzima-Nyarko, M., Radu, D., Bulajic, B., Lozancic, S. "Enhancing the seismic safety of upgraded RC buildings using FRP retrofitting: Analytical and field evidence from the 2023 Kahramanmaraş earthquakes", *Bulletin of Earthquake Engineering*, 24(3), pp. 1467–1501, 2026. <https://doi.org/10.1007/s10518-025-02338-z>
- [18] Salhi, M., Ben Addi, H., Boubekour, T. "Investigating the Performance of Self-compacting Concrete Exposed to Hot Weather", *Periodica Polytechnica Civil Engineering*, 69(1), pp. 251–262, 2025. <https://doi.org/10.3311/PPci.24092>
- [19] Işık, E., Karaçam, R., Harirchian, E., Hadzima-Nyarko, M. "Comparative Analysis of Post-Earthquake Damage and Structural Irregularities in RC Buildings: Field Evidence from the 2023 Kahramanmaraş (Türkiye) Earthquakes", *Buildings*, 16(6), 1140, 2026. <https://doi.org/10.3390/buildings16061140>

- [20] Işık, E. "A Study on Strengthening RC Structural Elements with Fibers Based Polymers", *Bitlis Eren Üniversitesi Fen Bilimleri Dergisi*, 14(2), pp. 1269–1286, 2025.
<https://doi.org/10.17798/bitlisfen.1675489>
- [21] Khatib, J. M. "Performance of self-compacting concrete containing fly ash", *Construction and Building Materials*, 22(9), pp. 1963–1971, 2008.
<https://doi.org/10.1016/j.conbuildmat.2007.07.011>
- [22] Iqbal, S., Ali, A., Holschemacher, K., Ribakov, Y., Bier, T. A. "Effect of Fly Ash on Properties of Self-Compacting High Strength Lightweight Concrete", *Periodica Polytechnica Civil Engineering*, 61(1), pp. 81–87, 2017.
<https://doi.org/10.3311/PPci.8171>
- [23] Karatas, M., Gunes, A. "Engineering Properties of Self-Compacting Concrete Produced by Polypropylene and Steel Fiber", *Periodica Polytechnica Civil Engineering*, 59(2), pp. 95–102, 2015.
<https://doi.org/10.3311/PPci.7348>
- [24] Karahan, Ş., Büyüksaraç, A., Işık, E. "The Relationship Between Concrete Strengths Obtained by Destructive and Non-destructive Methods", *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 44(1), pp. 91–105, 2020.
<https://doi.org/10.1007/s40996-019-00334-3>
- [25] Xiao, Z., Liu, Z., Guo, X., Liu, J. "An intelligent non-destructive method to identify the quality of self-compacting concrete based on convolutional neural networks via image recognition", *Case Studies in Construction Materials*, 22, e04442, 2025.
<https://doi.org/10.1016/j.cscm.2025.e04442>
- [26] Consiglio, A. N., Muciaccia, G., Rosati, G. "Evaluation of prestress losses in concrete beams using destructive and non-destructive methods", *Structural Concrete*, 27(4), pp. 5853–5873, 2026.
<https://doi.org/10.1002/suco.70454>
- [27] Hassan, M. "Critères découlant d'essais de charge pour l'évaluation du comportement des ponts en béton et pour le choix de la précontrainte" (Criteria derived from load tests for evaluating the behavior of concrete bridges and for selecting prestressing), PhD thesis, École Polytechnique Fédérale de Lausanne, 1994. (in French)
- [28] Gere, J. M., Goodno, B. J. "Mechanics of Materials", Cengage Learning, 2012. ISBN 9781285225784
- [29] Beer, F. P., Johnston Jr., E. R., DeWolf, J. T., Mazurek, D. F. "Mechanics of Materials", McGraw-Hill Education, 2015. ISBN 978-0-07-339823-5 [online] Available at: [https://dr-mirjalili.ir/download/uploads/books/Mechanics-of-Materials-7th-edition-\[www.mirjalili.net\].pdf](https://dr-mirjalili.ir/download/uploads/books/Mechanics-of-Materials-7th-edition-[www.mirjalili.net].pdf) [Accessed: 01 April 2026]
- [30] ASTM International "ASTM C597-16 Standard Test Method for Pulse Velocity Through Concrete", ASTM International, West Conshohocken, PA, USA, 2016.
<https://doi.org/10.1520/C0597-16>
- [31] Rojas-Henao, L., Fernandez-Gomez, J., Lopez-Aguí, J. C. "Rebound Hammer, Pulse Velocity, and Core Tests in Self-Consolidating Concrete", *ACI Materials Journal*, 109(2), pp. 235–243, 2012.
<https://doi.org/10.14359/51683710>
- [32] Mavko, G., Mukerji, T., Dvorkin, J. "The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media", Cambridge University Press, 2009. ISBN 978-0-521-86136-6
- [33] Dickson, G. "Ultrasonic Methods for Determination of Mechanical Properties of Dental Materials", National Bureau of Standards, Washington, DC, USA, Rep. 10 177, 1969.
<https://doi.org/10.6028/NBS.RPT.10177>
- [34] Achenbach, J. D. "Wave Propagation in Elastic Solids", North-Holland Publishing Company, 1973. ISBN 0 7204 2367 8 [online] Available at: https://api.pageplace.de/preview/DT0400.9781483163734_A23875053/preview-9781483163734_A23875053.pdf [Accessed: 01 April 2026]
- [35] Feldman, R. F. "CBD-187 Non-Destructive Testing of Concrete", National Research Council of Canada. Division of Building Research, Ottawa, Canada, 1977.
<https://doi.org/10.4224/40000715>
- [36] Facaoaru, I. "Non-Destructive Testing of Concrete in Romania", In: *Proceedings of the Symposium on Non-Destructive Testing of Concrete and Timber*, Institution of Civil Engineers, London, UK, 1969, pp. 39–49. ISBN 978-0-7277-4468-5
<https://doi.org/10.1680/ntocats.44685.0007>
- [37] Groupe Industriel des Ciments d'Algérie (GICA) "CEM II/A-L 42.5 Portland-composite cement", Technical Product Data Sheet, Mascara Cement Plant, Mascara, Algeria. [online] Available at: <https://gica.dz/fr/> [Accessed: 01 September 2025]
- [38] IANOR "NA 442:2013—Ciments: Composition, spécifications et critères de conformité des ciments courants" (NA 442:2013—Cements: Composition, specifications and conformity criteria for common cements), Institut Algérien de Normalisation (IANOR), Algiers, Algeria, 2013. (in French)
- [39] CEN "EN 197-1:2011 Cement - Part 1: Composition, specifications and conformity criteria for common cements", European Committee for Standardization, Brussels, Belgium, 2011.
- [40] Samir, B., Snouci, T. A., Youcefi, A., Mohamed, Z., Sid Mohamed, B. "Effect of Steel Fibers on the Mechanical Properties of Mortars", *Community Practitioner*, 63(2), pp. 74–81, 2024.
<https://doi.org/10.5281/zenodo.10967729>
- [41] Entreprise Nationale des Granulats (ENG) "Dolomitic limestone filler", ENG, Tlemcen, Algeria, Technical Product Data, 2025.
- [42] GRANITEX "MEDAFLOW 3041 R – Superplastifiant haut réducteur d'eau pour béton" (MEDAFLOW 3041 R – High water-reducing superplasticizer for concrete), GRANITEX, Algiers, Algeria, Technical Product Data Sheet, Version 3, 2017. (in French)
- [43] Guelta and Kboba Quarries "Natural aggregate supply for concrete production", Guelta and Kboba Quarries, Tiaret, Algeria, Technical Report, 2024.
- [44] Kedjour, N. E. "Le laboratoire du béton" (Concret Laboratory), Office des Publications Universitaires (OPU), 2003. ISBN 9961-0-0596-1 (in French)
- [45] Proceq SA "Pundit Link software for Pundit Lab ultrasonic instruments, (2.4.4)", [computer program] Available at: <https://www.screeningeagle.com/en/download/> [Accessed: 01 April 2026]
- [46] International Atomic Energy Agency (IAEA) "Guidebook on Non-Destructive Testing of Concrete Structures", Training Course Series No. 17, IAEA, Vienna, Austria, 2002. [online] Available at: <https://www.iaea.org/publications/6347/guidebook-on-non-destructive-testing-of-concrete-structures> [Accessed: 01 April 2026]