construction materials

Article

Physical and Mechanical Properties of Reinforced Concrete from 20th-Century Architecture Award-Winning Buildings in Lisbon (Portugal): A Contribution to the Knowledge of Their Evolution and Durability

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Abstract: The use of concrete materials in Portugal, namely reinforced concrete, began in the 19th century. However, during the 20th century, the increase in the application of this composite material, alongside the use of hydraulic binders, led to a disruption of traditional construction techniques and enhanced generalized application in concrete structures, combining aesthetics with functionality. In this paper, the authors will present and discuss several physical and mechanical characteristics of reinforced concrete materials from 12 award-winning architectural buildings constructed between the 1930s and the end of the 20th century in Lisbon, Portugal. These results are vital to evaluate their durability, as those buildings have an undiscussable heritage value in the context of 20th-century buildings' valorization. Furthermore, the results will contribute to the knowledge of the current state of conservation of these materials and will allow an understanding of the evolution in the application of national regulations during this period.

Keywords: concrete; award-winning buildings; 20th century; heritage; Lisbon; durability; national regulations

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1. Introduction

Reinforced concrete elements are an essential part of the building structures of the 20th century. In the context of enhancing and preserving built heritage, it is increasingly necessary to know the characteristics of this composite material since little is known about the criteria of the constructive design of a significant proportion of the buildings built in the early 20th century.

However, there has been concern about studying reinforced concrete structures in the international context. These studies often relate construction materials to construction methods, manufacturing processes, performance associated with applying standards, or by approaching their context from the perspective of historical appreciation. Some of them may be exemplified by several works [1–5].

Maintaining concrete structures to extend their service life is a mandatory condition. For the structural integrity of the buildings, durability is a critical factor.

The durability of reinforced concrete structures depends on several factors, such as weathering action, chemical attack, and abrasion, while maintaining its desired design properties. It usually refers to the duration of the life span of trouble-free performance. According to Mather [6], concrete is "durable" if, in its environment, it has provided the desired service life without the high cost of maintenance and repair due to degradation or deterioration.

The evolution of construction processes during the 20th century, associated with the massification of the use of Portland cement, forced the processes' standardization and the creation of national regulations. In 1918 the first Portuguese regulation on reinforced concrete was published [7], which allowed technological and broad harmonization of the use of this composite construction material. Until 1918, public construction was carried out according to the French regulations published in 1906 [7]. To understand the importance of the use of reinforced concrete at the beginning of the 20th century, more specifically between 1903 and 1911, we must mention the publication of the first regulations in various countries, such as Switzerland, Prussia, France, Italy, England, Austria, Russia, Denmark, and the United States [8–21].

In 1935, the so-called reinforced concrete regulation (*Regulamento do Betão Armado—RBA 1935*) [22] revoked the first published regulation. Between the publication of these two documents, which lasted about 17 years, the research and technology applied to increase the knowledge of this composite material have worldwide evolved enormously.

In Portugal, one of the aspects to highlight as an upgrade of regulation is the transition from the use of smooth to ribbed rebars, which was defined by the regulation of reinforced concrete structures published in 1967 (*Regulamento de Estruturas de Betão Armado—REBA 1967*) [23]. The use of plain rebars has implications for the efficiency of crack control and the fixing length. Compared to plain rebars, the ribbed steel ones have greater efficiency in controlling crack openings. After 1967, the Reinforced and Prestressed Concrete Structures regulations were published in 1983 (*Regulamento de Estruturas de Betão Armado e pré-esforçado—REBAP 1983*) [24].

In addition to the reinforced concrete structures regulations, regulations for hydraulic binder's concretes were published in 1971 [25] and 1989 [26], the latter being an updated version of the former. Hydraulic binder concretes are widely used in construction, assuming a relevant role in structures. For that reason, their characteristics and application conditions have a significant impact on the economy and safety of the works.

Table 1 display the concrete characteristics considered in the different regulations published and applied during the 20th century.

Table 1. Evolution of concrete characteristics through regulations applied in Portugal during the 20th century.

Regulations	Main Characteristics
Regulation of 1918	Prescribed dosage in the regulation: 300 kg of cement, 400 L of sand, and 800 L of gravel. There is no concept of resistance class. Minimum compressive strength: 120 kg/cm^2, at 28 days (through cubes).
RBA 1935	The dosage prescribed in the regulation (300 kg of cement, 400 L of sand, and 800 L of gravel). There is no concept of resistance class. Minimum compressive strength value: 180 kg/cm^2, at 28 days (through cubes).
REBA 1967	Resistance classes B180, B225, B300, B350 and B400 (compressive strength in kg/cm^2 = numeric part). Characteristic resistance in kg/cm^2 at 28 days (through cubes).
RBLH 1971 (updated by RBLH 1989)	Two types of concrete: B for resistance requirement and BD1, 2, and 3 for special durability requirement.
REBAP 1983	Resistance classes from B15 to B55, with the resistance increasing by 5 MPa to each class (compressive strength in Mpa = numeric part). Classes defined in international units (MPa). Characteristic strength in MPa (cubic test pieces).

The architectural quality of Lisbon buildings awarded with the Valmor Prize for Architecture [27–29], which is the object of this study, is of great patrimonial interest.

Thus, studying their construction materials is essential to support future conservation and restoration actions. This work does not intend to represent ordinary buildings but to understand and evaluate the advances achieved in each period of construction in Portugal during the 20th century, based on buildings of unquestionable architectural value, which, in general, were built using edge technology of their time. It is crucial to characterize the properties of the employed concretes using a methodology that allows us to provide a set of data regarding their physical and mechanical characteristics. These characteristics should be related to the existing regulations at the construction time and will allow us to infer the quality of the concretes applied.

Different authors have published several studies [30–32] demonstrating the importance of preserving reinforced concrete heritage since the beginning of the 20th century and applying appropriate methodologies to its investigation. A proper assessment of the properties of old concrete is needed to ensure the extended working life and the safe use of old facilities [30]. The study of physical and mechanical characteristics is critical to evaluating the performance of old structures, as demonstrated by Ambroziak et al. [30] in a study on the durability of a 95-year-old concrete built-in bridge. Sena-Cruz et al. [2] studied the physical and chemical characteristics of a reinforced concrete bridge built in 1907. Ambroziak et al. [31] studied the durability and strength of the reinforced concrete properties of a 70-year-old concrete structure in an office building. Sohail et al. [32] investigated the outcomes of concrete degradation in structural concrete elements in the harsh climates of the Arabian Gulf between the 1960s and the 1980s.

This work is part of a more extensive study comprising chemical, mineralogical, and microstructural characterization, whose data will complement the results presented here. The results will allow establishing criteria for maintenance and conservation of this heritage, contributing to its safeguard. The data obtained will also contribute to the knowledge of the evolution of materials in the built heritage of the 20th century, which is attracting more and more interest.

2. Materials and Methods

2.1. Case Studies and Sampling

Twelve buildings were studied (Table 2). The first award-winning building was prized in 1938, and the last one was prized in 2002. These buildings' main architectural and constructive characteristics can be found elsewhere [33–46]. The studied buildings do not present degradation signs that may affect their structural integrity, nor are they continuously monitored.

Concrete sampling was carried out in places that did not compromise the building's safety or aesthetics [47]. Samples were mainly taken from architectural and non-architectural reinforced concrete columns and walls using a diamond core driller equipped with a 75 mm diameter core bit (Figure 1). Due to technical constraints, sometimes core samples were collected at half the diameter, in which case, no mechanical tests were performed.

Table 2. Case studies, sampling zones and samples collected.

Case Study (Award Year)	Name	Image of the Case Study	Construction Year (Completion)	Sampling Zones (Interior/Exterior)	Structural Element	Number of Samples		Type of Coatings/Samples' Distance to the Surface
						Architectural Concrete	Non-Architectural Concrete	
IRF (1938)	*Nossa Senhora do Rosário de Fátima* Church		1938	Belltower (interior)	Columns	n.a.	4	Plasters and painting layers/up to 10 mm
DN (1940)	*Diário de Notícias* Building		1940	Basement. −2 floor (interior)	Columns	n.a.	4	Plasters/26 to 80 mm
LIP (1958)	Laboratories of Pasteur Institute of Lisbon		1957	1st floor. Chemical laboratory and technical area (interior)	Columns	n.a.	6	Painting layers/up to 1 mm
				2nd floor. West façade (exterior)	Beam	n.a.	1	Rendering mortar/7 mm
EUA53 (1970)	*América* Building		1969	Stairs. Between the 3rd and 4th floor (interior)	Wall	n.a.	1	Plasters/25 mm
				Corridor. 2nd-floor technical room (interior)	Column	n.a.	1	Plasters/25 mm

Table 2. *Cont.*

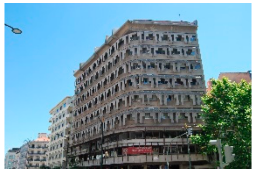
Case Study (Award Year)	Name	Image of the Case Study	Construction Year (Completion)	Sampling Zones (Interior/Exterior)	Structural Element	Number of Samples		Type of Coatings/Samples' Distance to the Surface
						Architectural Concrete	Non-Architectural Concrete	
FRAN (1971)	*Franjinhas* Building		1969	External gallery. East façade (exterior)	Column	1	n.a.	No coatings/0 mm
					Wall	1	n.a.	No coatings/0 mm
				Garage. −2 floor (interior)	Columns	4	n.a.	No coatings/0 mm
					Wall	1	n.a.	No coatings/0 mm
FCG (1975)	Calouste Gulbenkian Foundation Headquarters and Museum		1969	Auditorium ventilation shafts. −2 floor (interior)	Walls	n.a.	4	Plasters and painting layers/up to 10 mm
				Headquarters garage. Technical room. −2 floor (interior)		n.a.	3	Plasters/up to 35 mm
ISCJ (1975)	*Sagrado Coração de Jesus* Church		1970	7th-floor terrace (exterior)	Wall	1	n.a.	No coatings/0 mm
JRP (1987)	*Jacob Rodrigues Pereira* Institute		1987	Swimming pool surrounding area (interior)	Columns	n.a.	7	Painting layers/up to 1 mm

Table 2. *Cont.*

Case Study (Award Year)	Name	Image of the Case Study	Construction Year (Completion)	Sampling Zones (Interior/Exterior)	Structural Element	Number of Samples		Type of Coatings/Samples' Distance to the Surface
						Architectural Concrete	Non-Architectural Concrete	
PCV (1998)	The Knowledge Pavilion		1998	2nd-floor terrace (exterior)	White concrete walls	4	n.a.	No coatings/0 mm
				Ground floor. South façade (exterior)		2	n.a.	No coatings/0 mm
				Garage. −1 floor (interior)	Columns	n.a.	4	Plasters/up to 5 mm
				Technical room. −1 floor (interior)		n.a.	2	Plasters/up to 5 mm
C8 (2000)	C8 Building (Faculty of Sciences of the University of Lisbon)		2000	1st floor. Structure A (interior)	Walls	n.a.	1	Painting layers/up to 1 mm
				1st floor. Structure B (interior)		n.a.	2	Painting layers/up to 1 mm
				1st floor. Structure C (interior)		n.a.	1	Painting layers/up to 1 mm
				1st floor. Structure D (interior)		n.a.	2	Painting layers/up to 1 mm
AS (2001)	*Atrium Saldanha* Building		1997	5th floor. Hub 2 (interior)	White concrete column	2	n.a.	No coatings/0 mm
				Garage. −4 floor (interior)	Column	1	n.a.	No coatings/0 mm
					Walls	5	n.a.	No coatings/0 mm
UNL (2002)	Rectory of the New University of Lisbon		2002	Air treatment unit. 1st-floor (interior)	Walls	n.a.	2	Plasters/up to 30 mm
				Ground floor storage (interior)		1	n.a.	No coatings/0 mm
				Garage. −1 floor (interior)	Earth supporting walls	1	n.a.	No coatings/0 mm
				Garage. −2 floor (interior)		2	n.a.	No coatings/0 mm

Notation: n.a.—not applicable.

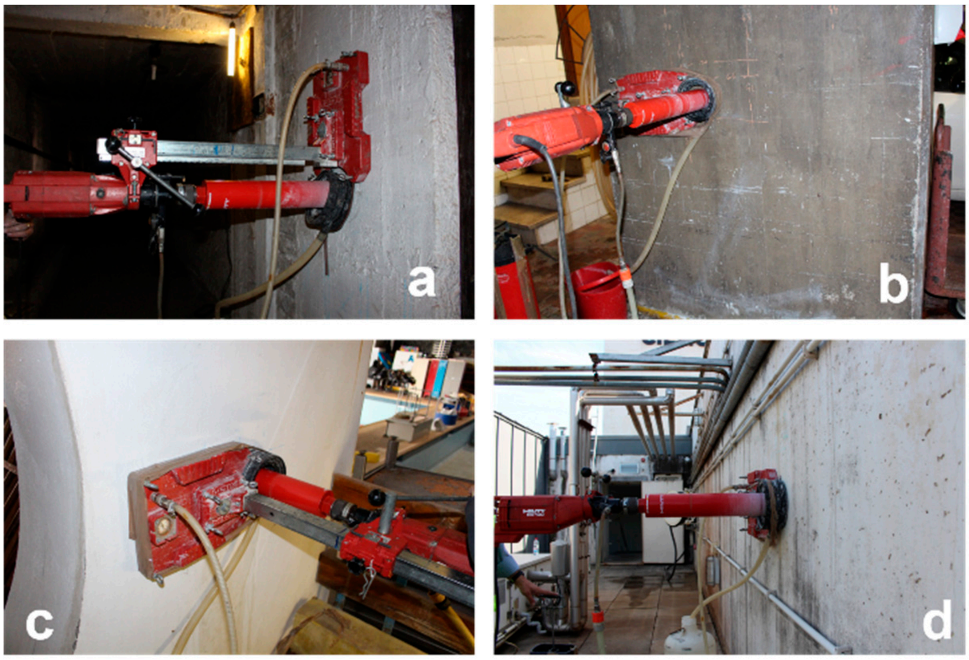


Figure 1. Images of concrete sampling campaign: (**a**) IRF (1938); (**b**) FRAN (1971); (**c**) JRP (1987); (**d**) PCV (1998).

2.2. Characterization Methodology

The characterization methodology included observing samples to record the evolution of the dimension of the largest crushed aggregates over time. This evolution is essential to relate it to physical characteristics, such as the compacity, which is also assessed through ultrasonic pulse velocity tests and water absorption by capillary rising, open porosity, and bulk density tests. Carbonation depth was directly measured in core samples so that it can be correlated to the mechanical and physical properties. The mechanical behavior was evaluated through compressive strength and dynamic modulus of elasticity in compression tests to determine their evolution over the analyzed period. Finally, to evaluate the quality of the concrete, the compressive strength results were used to estimate by modelling, through the application of Eurocode 2 [48], the corresponding compressive strengths at 28 days.

Considering the proposed characterization methodology, most of the samples collected are over 150 mm long. As the availability of samples was limited, the core samples were cut in half, and the ends rectified to reach a flat surface and regular dimension. In these cases, capillary water absorption, open porosity and bulk density tests were performed on one of the specimens. Ultrasonic pulse velocity and compressive strength tests were performed in the other specimen, with a length/height equal to the diameter. The dynamic modulus of elasticity in compression was performed on other samples with 150 mm in length, also with the rectified ends.

Figure 2 refer to the main apparatus and testing machines used during the testing campaign. Figure 2a show a tray filled with samples during the water absorption by the capillary rise test. Figure 2b display a weighing apparatus used to estimate the hydrostatic mass during the evaluation of open porosity and bulk density. Figure 2c show a portable ultrasonic pulse velocity tester, and Figure 2d,e exhibit, respectively, the compressive strength and dynamic elastic modulus test machines.

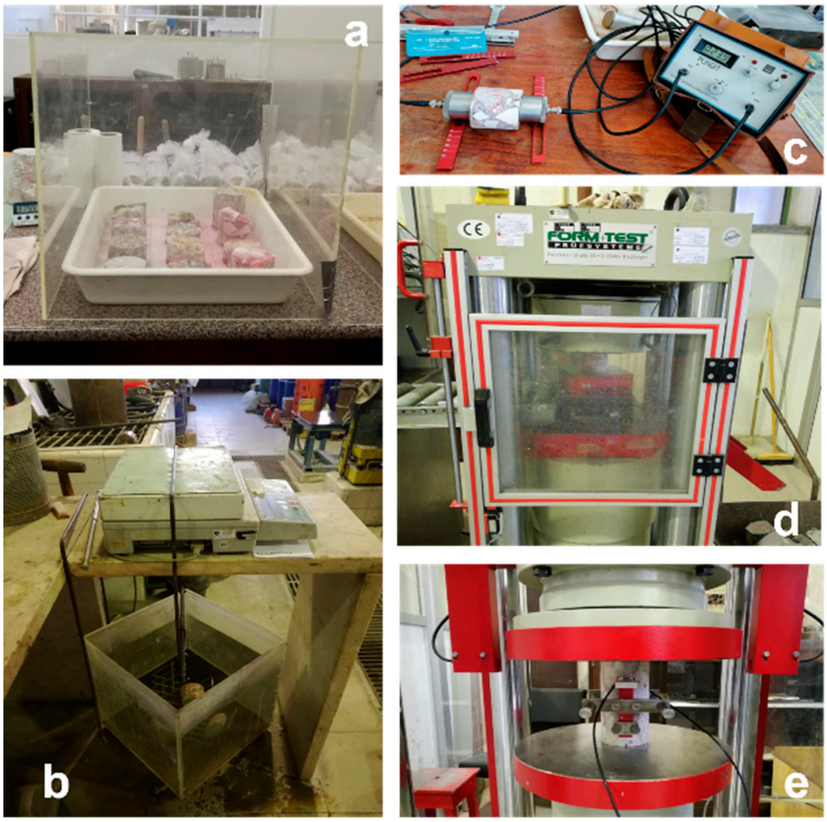


Figure 2. Apparatus for concrete testing: (**a**) capillary water absorption test; (**b**) open porosity and bulk density; (**c**) ultrasonic pulse test; (**d**) compressive strength test; (**e**) dynamic elastic modulus test.

2.2.1. Macroscopic Observation of Cores and Carbonation Depth Assessment

After sampling, the cores were photographed and macroscopically observed to register some characteristics, such as the type of coarse aggregates, presence of cracks, gels, and deposits. The size of the largest coarse aggregates was measured with a digital caliper, and the concrete carbonation depth was measured by applying a phenolphthalein alcoholic solution directly to the core samples [49], whose results have already been published elsewhere [46].

2.2.2. Capillary Water Absorption Test

The water absorption by capillary rise was determined according to LNEC Specification E393 [50]. The test protocol consists of drying a concrete sample, placing it in an oven at a temperature of 40 ± 5 °C for 14 days, and weighing the initial mass (*M0*). Then, the sample is placed inside a tray, filling it carefully with water until the level reaches 5 ± 1 mm above the lower face of the sample, avoiding wetting the other faces.

The tray and the samples were covered with a hood to keep the water level constant during the entire test. The measurements (*Mi*) are made at regular time intervals. To calculate the capillary absorption at a given time, divide the mass increase (*Mi-M0*) by the sample area in contact with the water.

2.2.3. Open Porosity and Bulk Density Test

The open porosity corresponds to the water absorption by immersion under a vacuum. The water absorption test [51] was performed after drying the samples at a temperature of 105 °C until a constant mass was obtained (*Md*). The samples were placed in a receptacle in a vacuum chamber in which the air pressure was brought down to an absolute value of not more than 1 kN/m^2 and held in a vacuum for 24 h. Water was then slowly introduced into the chamber so that the samples were completely immersed, maintaining the 0 for

24 h. The samples were kept immersed for another 24 h at atmospheric pressure and then weighed in water to obtain the hydrostatic mass (*Mh*). Finally, the samples were removed from the water, and their surface was dried rapidly with an absorbent cloth or a natural sponge to remove all surface water to be weighed (*Ms*) to obtain the mass of the saturated samples in a vacuum.

The open porosity (P_0) was then calculated according to the following Equation (1)

$$P_0 = \frac{Ms - Md}{Ms - Mh} \times 100 \tag{1}$$

The bulk density (*Pb*) was calculated according to the following Equation (2).

$$Pb = \frac{Md}{Ms - Mh} \times \rho \tag{2}$$

ρ is the water volumetric mass density at room temperature.

2.2.4. Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity test was carried out according to EN 12504-4 [52]. Ultrasonic pulse velocity (V) was determined directly using a PUNDIT 6 portable ultrasonic non-destructive tests of CNS electronics, with a measurement range from 0.1 µs to 9999 µs, which has two transducers working in a 54 kHz frequency, placed at the ends of the sample. The velocity of propagation is calculated by the following Equation (3).

$$V = \frac{L}{T} \tag{3}$$

where L is the path length, and T is the time it takes for the ultrasonic pulse to traverse the path length.

The samples were previously rectified by grinding to obtain flat end surfaces. As the grinding was carried out with a water aid, the samples were dried in an oven at 40 °C for 72 h before the test.

2.2.5. Compressive Strength and Dynamic Modulus of Elasticity in Compression

The compressive strength test was performed according to the EN 12390-3 [53] procedure in a FORM+TEST STM 3000 S testing machine featuring a maximum test load of 3000 kN.

The modulus of elasticity in compression was carried out according to E397-1993 [54] in a FORM+TEST Alpha 20–600 testing machine. The test equipment applies and maintains the required load with an accuracy of not less than 1%. The instruments for measuring changes in length (the strain transducers) were placed at equal distances from the ends of the test piece and at least 1/4 of the height from the ends. The measuring instruments enabled the length to be determined with an accuracy of not less than 5×10^{-6}.

A constant load speed within the range of 0.6 ± 0.2 MPa/s was applied. The load was increased continuously, starting from 0.5 MPa until it reached 1/3 of the rupture strain, which was known after the compressive strength test was carried out in other samples of the same building. Six loading cycles were carried out for each test.

2.2.6. Quality Evaluation of the Hardened Concrete

The standard CEN EN 1992: Eurocode 2 [48] was applied to calculate the compressive strength that concrete would have at 28 days of age, considering the concrete class prescribed in the construction design project for each case study [46] and thus evaluating the quality of construction at the time of concrete application.

For this calculation, Equation (4) was used. It was deduced from Equations (5) and (6) of the CEN EN 1992: Eurocode 2, where $f_{ck}(28d)$ is the characteristic value of the compressive strength applied in structures and $f_{cm}(28d)$ is the value obtained by applying

Equation (5) takes into account a standard deviation of 4 MPa, which was considered current in older concrete productions.

$$f_{ck}\,(28d) = f_{cm}(28d) - (1.64 \times 4) \tag{4}$$

$$f_{cm} = f_{cm}(t)\,\beta_{cc}(t)^{-1} \tag{5}$$

with

$$\beta_{cc}(t) = \exp\left\{ s\left[1 - \left(\frac{28}{t}\right)^{1/2}\right]\right\} \tag{6}$$

where f_{cm} is the mean compressive strength at 28 days and $f_{cm}(t)$ is the compressive strength obtained by the test, with t being the buildings' age expressed in days. $\beta_{cc}(t)$ is the coefficient that depends on the age of the concrete t, and s is the coefficient that depends on the type of cement. Since the type of cement used in the production of the concrete is not known, a coefficient s = 0.20 was adopted, according to the CEN EN 1992 standard [41], as older cement presented slower strength increases compared to nowadays.

For both IRF (1938), DN (1940), and LIP (1958) case studies, the presented results of compressive strength at 28 days equals f_{cm} (the mean value). Since the concrete class was prescribed in the construction, the design was defined according to the 1935 regulation [22]. For the definition of the strength limits to be applied, this regulation refers only to minimum values of compressive strength, while in later regulations [23,24], which were applied in the remaining case studies, strength classes are defined using the criterion of the characteristic strength value f_{ck}.

3. Results and Discussion

3.1. Macroscopic Observation of Cores and Carbonation Depth

The macroscopic observation of the concrete cores showed large coarse aggregates composed of white limestone, sometimes fossiliferous, and rarely clayey (Figure 3). The first case study, IRF (1938), exhibited coarse volcanic aggregates, and the second one, DN (1940), also had chert aggregates. Most of these aggregates are compatible with the lithotypes explored to the north of the Lisbon region. No gels, deposits, or cracks were detected in the samples.

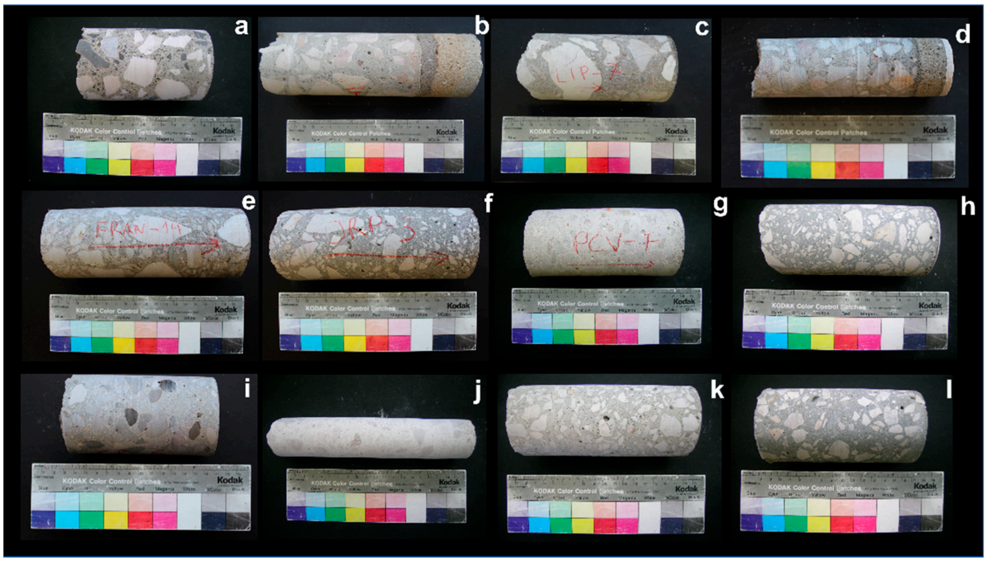


Figure 3. Sample cores from the following case studies: (**a**) IRF (1938); (**b**) DN (1940)—coated with plasters; (**c**) LIP (1958)8; (**d**) EUA53 (1970)—coated with plasters; (**e**) FRAN (1971); (**f**) JRP (1987); (**g**) PCV (1998)—white concrete; (**h**) PCV (1998); (**i**) C8 (2000); (**j**) AS (2001)—white concrete; (**k**) AS (2001); (**l**) UNL (2002).

The average dimension of the largest aggregate (Table 3) showed a reduction during the analyzed period, as displayed in Figure 4. The maximum values were recorded in LIP (1958) concretes. Their reduction started in the late 1960s, as exemplified by the FCG (1975), following the regulations [23,25]. The 1935 regulation [22] limited the maximum size to 40 mm, except for significant elements and massive structures where the coarse aggregates could be larger. The subsequent national regulation to recommend aggregates' dimension criteria was published in 1971 [25]. It mentioned using a maximum dimension of 38.1 mm, should the dimension be lower when the reinforcement would be dense. After these two decrees, further regulation [24] established dimension criteria depending on the reinforcement design.

Table 3. Dimension of the largest aggregate.

Parameters	Gray Concrete												White Concrete	
Case study	IRF (1938)	DN (1940)	LIP (1958)	EUA53 (1970)	FRAN (1971)	ISCJ (1975)	FCG (1975)	JRP (1987)	PCV (1998)	C8 (2000)	AS (2001)	UNL (2002)	PCV (1998)	AS (2001)
Average dimension (mm)	50.0	42.5	60.3	50.0	46.0	45.0	30.6	32.9	30.0	24.7	22.7	22.5	11.7	22.5
S.D. (σ)	8.2	2.9	17.4	14.1	17.2	2.5	3.5	11.0	6.3	4.5	2.6	5.2	2.6	3.5

Notation: S.D.—standard deviation.

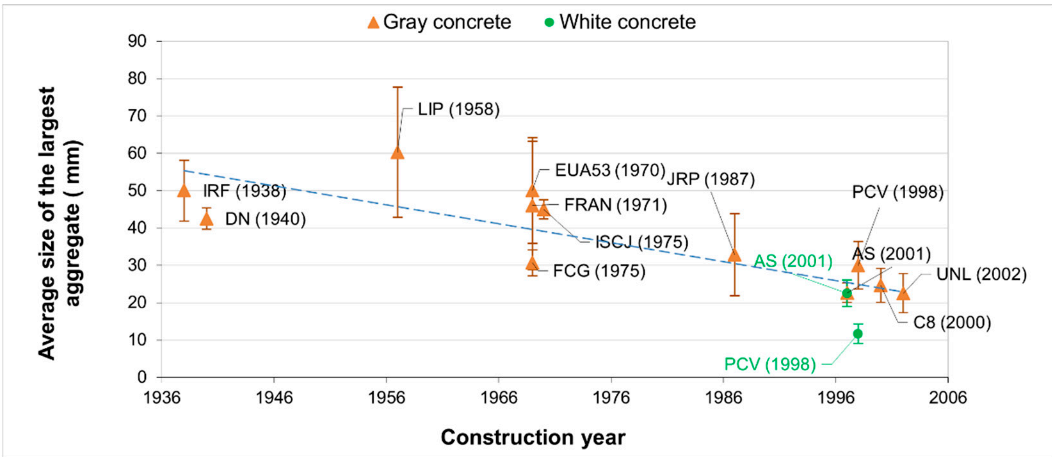


Figure 4. Evolution of the largest aggregate dimension over the period analyzed.

The carbonation depth (Table 4 and Figure 5) of architectural and non-architectural concrete shows a decreasing trend over time, which is expected with concrete ageing.

Table 4. Carbonation depth in the architectural and non-architectural concrete samples.

Parameters	Non-Architectural Concrete									Architectural Concrete				
Case study	IRF (1938)	DN (1940)	LIP (1958)	EUA53 (1970)	FCG (1975)	JRP (1987)	PCV (1998)	C8 (2000)	UNL (2002)	FRAN (1971)	ISCJ (1975)	PCV (1998)	AS (2001)	UNL (2002)
Carbonation depth (mm)	26.9	10.5	15.3	1.2	1.5	12.2	15.8	6.1	16.8	11.4	10.7	2.5	2.6	15.2
S.D. (σ)	10.4	10.2	9.4	1.2	0.5	8.3	9.9	4.2	8.7	6.6	5.1	2.1	1.8	5.7

Notation: S.D.—standard deviation.

The size reduction of crushed coarse aggregate over time is a consequence of the standardization and the optimization of the mixing control. The coarse aggregate plays a vital role in determining the mechanical behavior of concrete as it occupies about 70% of the concrete volume [55,56]. The mechanical properties of concrete from older case studies may be conditioned by the volume occupied by these aggregates and, consequently, by the interfacial zone (ITZ) area, which might evolve to the formation and propagation of microcracks. Similarly, the carbonation depth, which also tends to decrease towards the end of the analyzed period, may be favored by the development of microcracking in the dependence on the ITZ. Concretes from the oldest case study, IRF (1938), have a higher carbonation depth than any other, which is understandable, presumably due to the more prolonged exposure to CO_2. The carbonation depths of other concretes are quite variable due to the protection provided by the coatings. The coatings, whose typology, thickness (Table 1), and the related physical and chemical properties provided different types of protection, conditioned the penetration of CO_2 and the moisture transport capability.

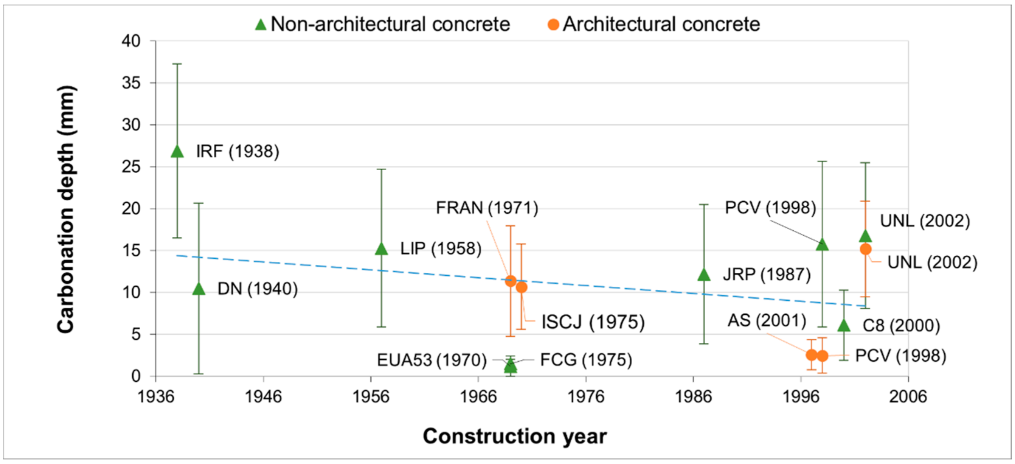


Figure 5. Evolution of the carbonation depth over the analyzed period.

3.2. Physical Characterization

Table 5 show the results of the physical characterization obtained for the open porosity, the ultrasonic pulse velocity, and water absorption by capillary tests.

Table 5. Average results of physical properties of concrete samples.

Parameters	**Gray Concrete**												**White Concrete**	
Case study	IRF (1938)	DN (1940)	LIP (1958)	EUA53 (1970)	FRAN (1971)	FCG (1975)	ISCJ (1975)	JRP (1987)	PCV (1998)	C8 (2000)	AS (2001)	UNL (2002)	PCV (1998)	AS (2001)
P_0 (%)	13.78	13.38	10.82	11.60	13.02	13.64	n.a.	20.02	14.86	14.21	15.54	15.75	13.77	13.30
S.D. (σ)	1.51	2.14	1.61	n.a.	2.04	0.67	n.a.	2.60	1.30	0.53	0.41	0.78	n.a.	n.a.
Pb (kg/m^3)	2302.27	2286.01	2379.81	2363.18	2306.50	2279.22	n.a.	2110.31	2258.08	2267.04	2220.48	2229.24	2262.81	2300.23
S.D. (σ)	49.72	66.74	42.37	n.a.	61.87	22.99	n.a.	74.70	35.55	13.31	16.50	23.65	n.a.	n.a.
V (m/s)	4103.20	4093.41	4652.52	4512.94	4816.02	4853.85	n.a.	3792.04	4555.49	4415.99	4512.20	4862.32	4684.49	4406.98
S.D. (σ)	805.37	270.77	169.43	n.a	297.55	180.46	n.a.	456.72	124.04	207.92	102.79	191.88	n.a.	n.a.
W.A. at 15 min (Kg/m^2)	1.18	1.27	1.16	0.41	0.61	0.46	n.a.	1.45	0.51	0.68	0.58	0.40	0.55	0.45
S.D. (σ)	0.01	0.93	0.47	n.a.	0.18	0.14	n.a.	0.49	0.10	0.16	0.15	0.08	n.a.	n.a.
W.A. at 60 min (Kg/m^2)	1.88	1.97	1.80	0.74	0.93	0.76	n.a.	2.52	0.84	1.15	0.97	0.61	0.90	0.91
S.D. (σ)	0.05	1.36	0.55	n.a.	0.24	0.21	n.a.	0.84	0.18	0.29	0.18	0.12	n.a.	n.a.
W.A. at 1440 min = 24h (Kg/m^2)	5.41	4.45	3.63	3.15	2.64	2.09	n.a.	9.13	2.48	4.19	3.47	1.61	2.71	3.33
S.D. (σ)	1.29	1.40	0.52	n.a.	0.67	0.49	n.a.	2.35	0.60	1.11	0.58	0.42	n.a.	n.a.

Notation: P_0—open porosity; S.D.—standard deviation; *Pb*—bulk density; *V*—ultrasonic pulse velocity; W.A.—water absorption by capillary rising; n.a.—not available.

The combined results show that the average of the open porosity values varies between 10.82% and 20.02%. The slight increasing trend over the period under analysis is shown in Figure 6.

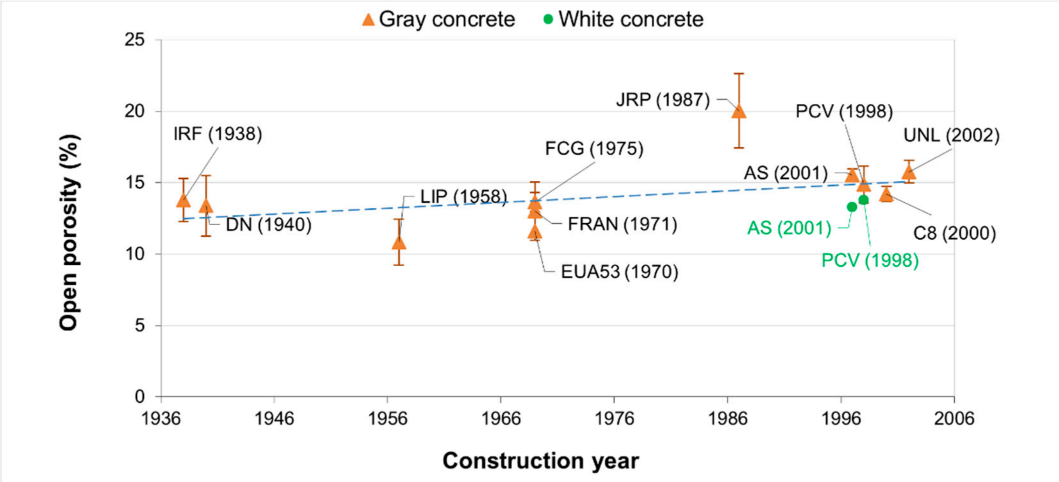


Figure 6. Evolution of the open porosity over the analyzed period.

Regarding the average ultrasonic pulse velocity, the results point to the quality of concrete material in a range between good and excellent, considering the classification of Whitehurst, 1951 [57]. The most significant variations in the results were observed in the case studies IRF (1938) and JRP (1987), as shown in Figure 7. In the first case, coarser aggregates may explain such variations. In contrast, in the second case, the higher open porosity influences the obtained result, resulting in the lower value of ultrasonic pulse velocity and, therefore, the compacity.

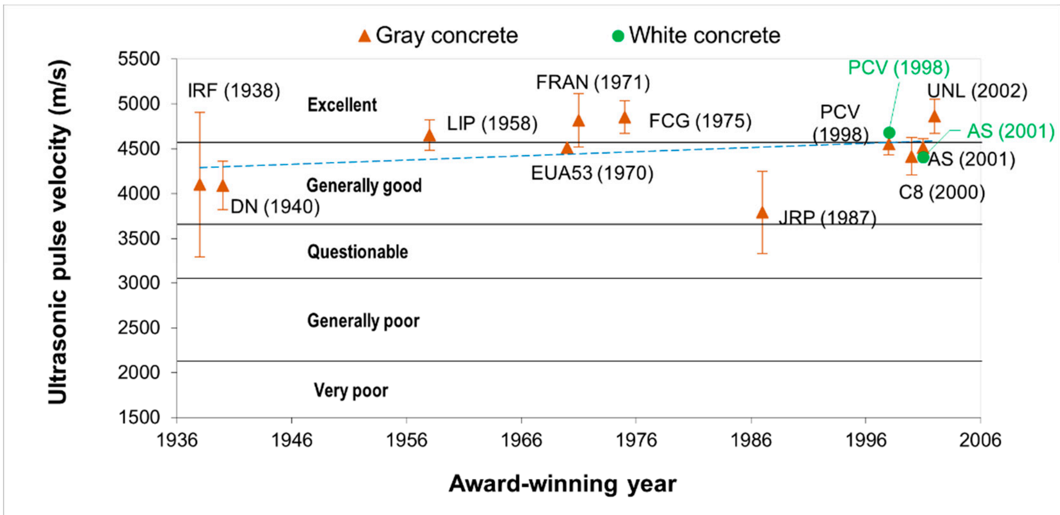


Figure 7. Evolution of the ultrasonic pulse velocity over the analyzed period. Quality classification according to [57].

The water absorption results by capillarity also show a reduction trend along the period under analysis (Figures 8 and 9). The concrete of the case study JRP (1987) shows the highest values of capillary absorption, corroborating the results of the high open porosity and the lowest values of bulk density and ultrasonic pulse velocity. Regarding white concretes, the values of capillary absorption are similar between samples of the two case studies analyzed (Figure 9): PCV (1998) and AS (2001).

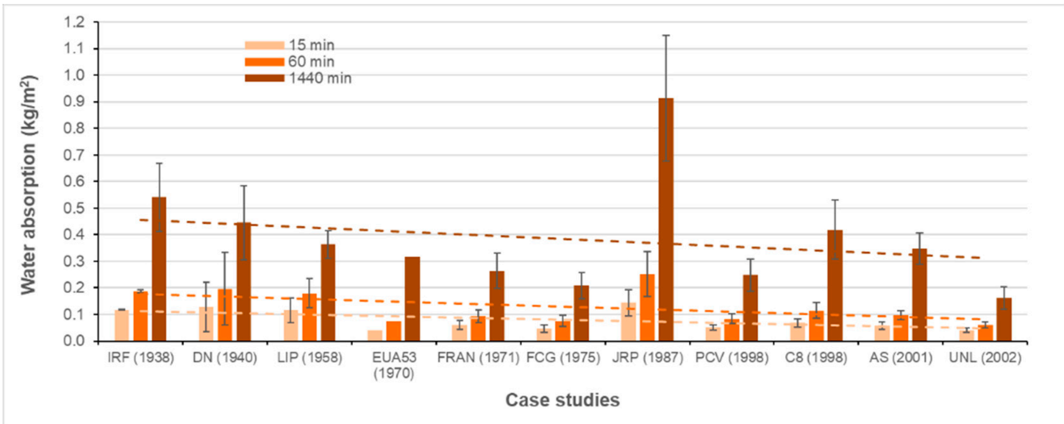


Figure 8. Capillary water absorption values at 15, 60, and 1440 min for gray concrete samples.

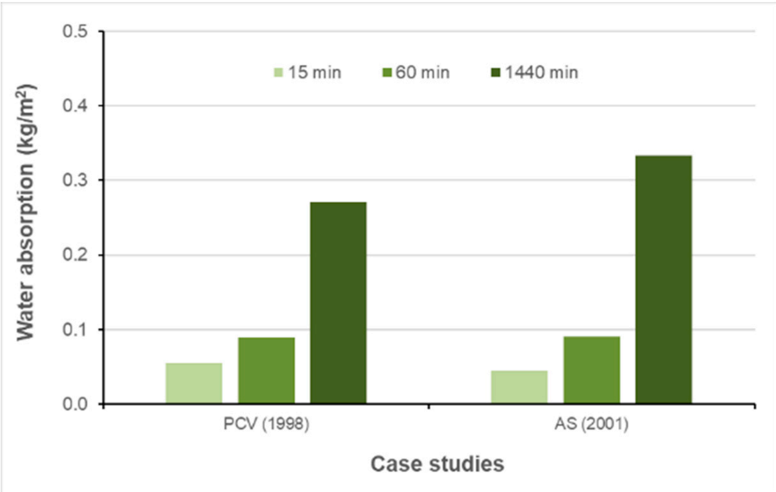


Figure 9. Capillary water absorption values at 15, 60, and 1440 min for white concrete samples.

The results of physical characterization show a tendency to reduce water absorption over time and, consequently, an increase in the compacity of the concrete, as proven by the results of the ultrasonic pulse velocity. The increase in ultrasonic pulse velocity is indicative of the reduction of the total porosity of the tested medium. However, the results obtained for the open porosity show an opposite trend, i.e., an increase over time, albeit slight. The reduction of the maximum size of the crushed aggregates and the greater homogeneity of the concrete favored the increase of compacity. On the other hand, there are exceptions, and the lowest values of open porosity were recorded in older concretes, which have coarse aggregates of larger dimensions. Variations in porosity and water absorption may be linked to cement type and dosage, as well to the volume occupied by the aggregates, namely the coarse aggregates, as it occurred in buildings constructed until the 1960s. The size-effect and the volume occupied by large aggregates in the tested specimens may be at the origin of this trend since the inherent porosity of these aggregates may significantly influence the results. It should be noted that limestones from the north region of Lisbon, one of the most extensive exploration centres in Portugal, present values of open porosity not exceeding 1.2% [58]. Nevertheless, a reduction in cement fineness is assumed over time [59,60]. It is observed that concretes with larger aggregates, more precisely those from buildings awarded up to 1998, usually show lower open porosities than concretes with smaller coarse aggregates. Hence, it can be assumed that the open porosity is influenced by the volume occupied by the coarse aggregates and their inherent low porosity.

From the point of view of the material's durability, the reduction in water absorption is a favorable outcome since it increases the resistance to sulphate attack [61] and may avoid the water ingress into concrete.

White cement should have identical behavior to its gray counterparts of the same type and strength class. As for physical characteristics, there are two differences directly related to each other: fineness and the beginning of the setting. White cement is generally thinner and has a greater specific surface. With greater cement fineness comes greater mechanical resistance, particularly at younger ages. On the other hand, as the cement is made of smaller particles, the amount of water required to achieve certain workability is higher, leading to an increase in porosity [42]. However, there was no open porosity increase compared to gray cement concrete for the same buildings.

3.3. Mechanical Characterization

The mechanical characterization results (Table 6) show a trend toward an increase in compressive strength and dynamic modulus of elasticity in compression throughout the period under analysis, as displayed in Figures 10 and 11. This trend is shown in any concrete, regardless of the structural element considered.

Table 6. Average results of mechanical tests of reinforced concrete samples.

Parameters	**Gray Concrete**													**White Concrete**	
	Superstructure												**S.W.**	**Superstructure**	
Case study	IRF (1938)	DN (1940)	LIP (1958)	EUA53 (1970)	FRAN (1971)	FCG (1975)	ISCJ (1975)	JRP (1987)	PCV (1998)	C8 (2000)	AS (2001)	UNL (2002)	UNL (2002)	PCV (1998)	AS (2001)
f_c (MPa)	28.30	32.10	35.80	n.a	60.43	69.58	n.a	27.17	57.13	60.20	61.90	67.47	76.10	65.00	n.a
S.D. (σ)	4.81	n.a	7.39	n.a	9.46	14.90	n.a	13.32	7.03	14.45	2.26	4.42	n.a	n.a	n.a
E_c (GPa)	18.50	17.30	28.60	n.a	33.80	37.20	n.a	17.55	34.37	28.10	31.63	37.50	n.a	35.50	n.a
S.D. (σ)	n.a	n.a	0.71	n.a	1.70	1.57	n.a	9.40	1.96	n.a.	0.81	0.00	n.a	n.a	n.a

Notation: S.W.—supporting walls; f_c—compressive strength; S.D.—standard deviation; E_c—dynamic modulus of elasticity; n.a.—not available.

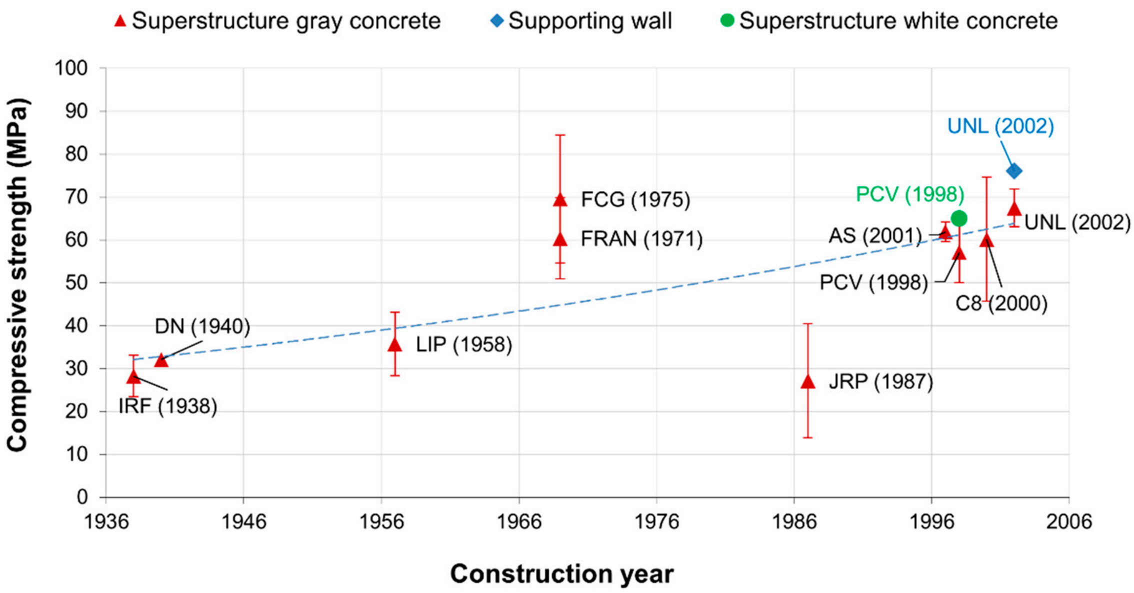


Figure 10. Evolution of the compressive strength over the analyzed period.

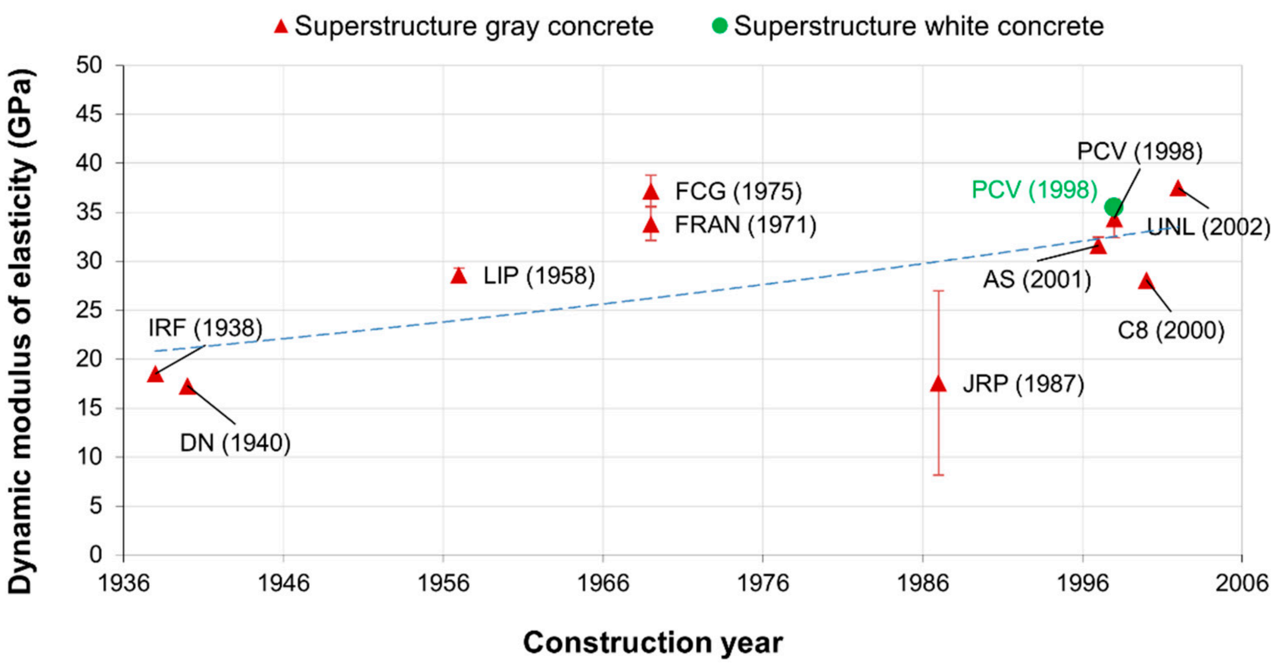


Figure 11. Evolution of the dynamic modulus of elasticity in compression over the analyzed period.

The maximum values of the mechanical characteristics were obtained in the UNL (2002) case study, followed by FCG (1975), respectively, 76.10 MPa and 69.58 MPa—compressive strength values. Dynamic modulus of elasticity values for both case studies are, respectively, 37.50 GPa and 37.2. The case study JRP (1987), on the contrary, presents the lowest values of these characteristics, registering 27.17 MPa and 17.55 GPa, respectively, for compressive strength and the dynamic modulus of elasticity.

It is reported that the compressive strength of concrete increases with the increase of the coarse aggregate size [56]. This relationship was not verified in this study since one or more types of concrete with different characteristics and strength classes were employed in each case study. However, the increasing trend of the compressive strength throughout the period under study accompanies the increase in compacity and the decrease in water absorption. All these properties are pore size structure-dependent, whereas an increase in the fineness of the cement or a decrease in the water to cement ratio (w/c) are expected to occur throughout the 20th century [1]. An evolutive correlation between compressive strength and open porosity shows no clear relationship (Figure 12).

The most relevant source of porosity refers to w/c. When this ratio becomes higher, the porosity of the cement paste in the concrete also upsurges, and the compressive strength reduces as the porosity increases. It is not possible to state a cause–effect relationship between porosity and compressive strength of the concretes up to the 1960s case studies. The concretes of the award-buildings until the 1960s have the larger crushed aggregates. The porosity should be influenced by the coarse aggregate's porosity, resulting in a decrease in the open porosity of the concrete. On the contrary, this relationship is observed in the concrete of the building JRP (1987).

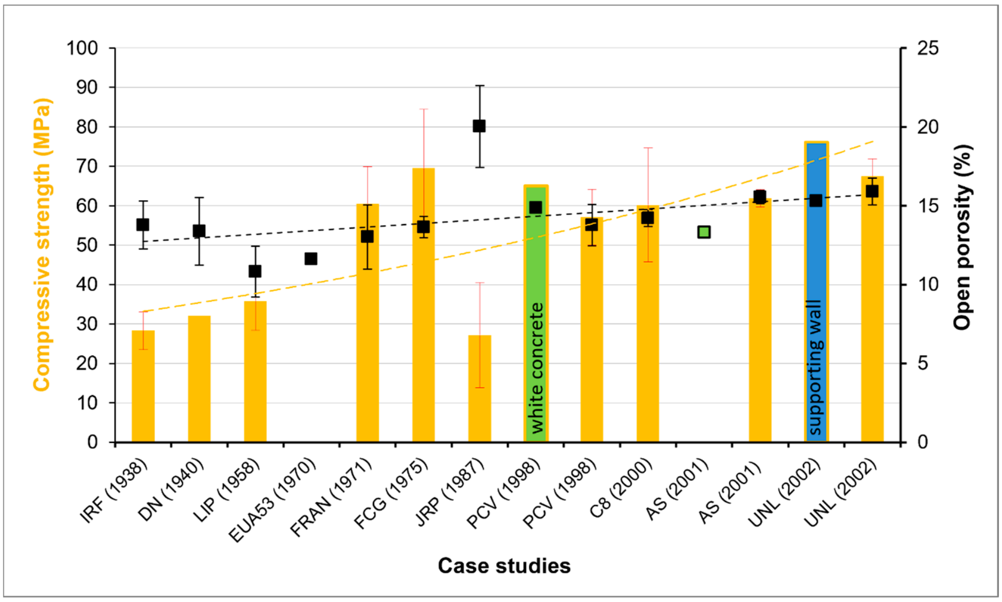


Figure 12. Correlation between compressive strength (bars) and open porosity (black squares) of superstructure white and gray concrete, and concrete from UNL (2002) supporting wall. Standard deviation of compressive strength is represented at the top of the bars by the red lines.

3.4. Quality Evaluation of the Hardened Concrete

The compressive strength was estimated for 28 days of curing, as described in Section 2.2.6, to assess the applied concrete materials' quality at the time of construction and their initial performance.

The results obtained indicate that most of the case studies would have a compressive strength higher than the prescribed at the construction time, as shown in Table 7 and Figure 13. Only two cases exhibited an estimated compressive strength lower than the prescribed: AS (2001) and JRP (1987). A difference of about 3 MPa was registered in the first case study, and the second revealed a difference of 9.5 MPa.

Table 7. Average results of mechanical properties of reinforced concrete samples.

Parameters	Gray Concrete												White Concrete
	Superstructure											S.W.	Superstructure
Case study	IRF (1938)	DN (1940)	LIP (1958)	FRAN (1971)	FCG (1975)	ISCJ (1975)	JRP (1987)	PCV (1998)	C8 (2000)	AS (2001)	UNL (2002)	UNL (2002)	PCV (1998)
t (days) *	30,295	29,565	23,360	18,980	18,980	18,615	12,410	8395	7665	8760	6935	6935	8395
Prescribed concrete class	(a)	(a)	(a)	B300	B300	B300	B225	n.a.	B30	B40	B30	B25	B35
β_{cc}	1.214	1.214	1.213	1.212	1.212	1.212	1.210	1.207	1.207	1.208	1.206	1.206	1.207
Prescribed compressive strength (MPa)	17.65	17.65	17.65	29.42	29.42	29.42	22.06	n.a.	30.00	40.00	30.00	25.00	35.00
f_{cm} (t) ** (MPa)	28.30	32.10	35.80	60.43	69.58	n.a.	27.17	57.13	60.20	61.90	67.47	76.10	65.00
f_{cm} (28d) (MPa)	19.81	22.48	25.09	42.36	48.81	n.a.	9.11	(b)	42.40	43.57	53.64	47.58	45.76
f_{ck} (28d) (MPa)	(c)	(c)	(c)	35.80	42.25	n.a.	12.55	(b)	35.84	37.01	47.08	41.02	39.20

Notation: S.W.—supporting walls; * building's age by the end of the year 2021 (considering the completion year of construction); n.a.—not available; ** tested compressive strength = f_c values in Table 6; (a) according to 1935 regulation [22]; (b) no result; (c) The regulation does not mention the characteristic value of the compressive strength, only the minimum value, which implies considering f_{cm} *(28d)* instead of f_{ck} *(28d)*.

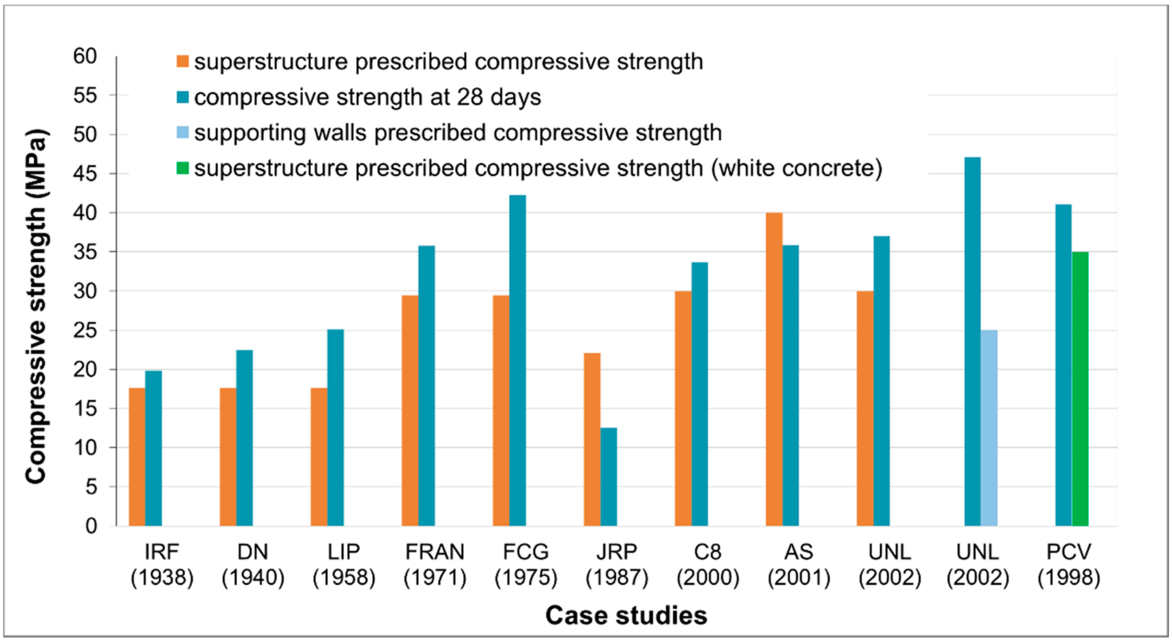


Figure 13. Prescribed compressive strength vs. calculated compressive strength at 28 days.

The concrete of the supporting walls of UNL (2002) presented the best performance, with a difference of 16.2 MPa between the prescribed and the calculated strength, followed by FCG (1975) with a difference of 12.8 MPa.

The evaluation of the concrete quality by estimating the compressive strength at 28 days of curing showed that the project design was followed up successfully. It demonstrates the great care taken during the construction process. It also highlights the actual condition of the structures, which enhances their durability. Although the AS (2001) case study shows a slight difference between the prescribed concrete compressive strength and the estimated one for 28 days of curing (<5 MPa), this difference is not as striking as in the JRP (1987) case study. All the physical and mechanical results obtained for JRP (1987) reveal a worse condition, as its performance is doubly different, which implies a questionable quality of the materials applied, corroborating the ultrasonic pulse velocity results whose dispersion of results places it in the range between the generally good to questionable quality class (Figure 7).

4. Conclusions

The present study made it possible to assess concrete's main physical and mechanical characteristics from a set of 20th-century award-winning architecture buildings in Lisbon. This study is a pioneer one on buildings that have an awarded architectural quality. The systematic studies on this kind of construction materials in Portugal are still scarce.

The results obtained point to an evolution in the characteristics over the period under analysis, which embodies the application of the national regulations. The physical and mechanical properties of the analyzed concrete materials reproduce an evolution towards the safety and durability requirements imposed by the national regulations on account of the advancement in the knowledge of structural performance and the scientific knowledge acquired throughout the 20th century.

The evolution of the physical and mechanical characteristics studied can be listed as follows:

1. The crushed coarse aggregate, mainly composed of limestone, had its maximum size reduced, having decreased from the late 1960s onwards, as exemplified by the case study FCG (1975), as set out in current Portuguese regulation by the time of construction.

2. The carbonation depth shows a decreasing trend, which is expected with concrete ageing. Although it is quite variable as the presence of coatings may play an important role.
3. The open porosity and bulk density values did not show very significant variations. A slight tendency towards a reduction in bulk density and increase in porosity may be related to the variation in the maximum size of the largest aggregate, which varies in the same direction as compacity.
4. Water absorption by capillary rising for all types of concrete studied (white and gray) does not show a consistent trend in the same direction as the open porosity.
5. Open porosity slightly increases towards the end of the analyzed period, implying that this is not exclusively due to the characteristics of the binder but to the whole composite material itself.
6. The mechanical characteristics, except for the building awarded in 1987, show a clear trend towards an increase in the values of the compressive strength and the dynamic modulus of elasticity.
7. Except for the building awarded in 1987, the estimation of the compressive strength at 28 days of curing showed that the project design had been accomplished.

The results allow us to conclude that, in general, the materials show a good durability condition, as far as the physical and mechanical characteristics point out to a good performance, not indicating degradation, considering the age of the buildings and that they are still in use. However, the 1987 award-winning building demonstrated that its overall performance could compromise durability, requiring monitoring actions to prevent degradation.

This study, being part of a more significant characterization underway, contributes to the necessary in-depth knowledge of the physical and mechanical characteristics to apply in conservation and restoration actions over the built heritage in the 20th century.

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