Artículo de Investigación

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Variability of the compressive strength of concretes used in buildings of Havana in the 20th century

Variabilidad De La Resistencia A Compresión De Los Hormigones Empleados En Edificaciones De La Habana En El Siglo XX

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RESUMEN

La evaluación de estructuras de hormigón armado depende de la correcta determinación de la resistencia a compresión del hormigón. La mayoría de las normativas exige que esta se estime mediante ensayos destructivos y no destructivos sobre la estructura. En algunos casos dicha estimación puede ser complementada con valores mínimos de resistencia por diseño de los hormigones de acuerdo a la época de construcción. En Cuba, que cuenta con un patrimonio de hormigón armado de más de 100 años, no se cuenta con este tipo de información. Por esa razón este trabajo tiene como objetivo principal caracterizar la resistencia a compresión de las estructuras existentes en La Habana, a partir de una base de datos de más de 1960 testigos extraídos de más de 160 edificaciones construidas en la ciudad en el siglo XX. La caracterización es realizada en términos de valores medios y de coeficientes de variación, en seis segmentos del siglo XX. Finalmente se ajustaron los valores de resistencia media a compresión a las distribuciones de probabilidad normal y log-normal, obteniendo valiosa información tanto para la evaluación de estructuras individuales como para estudios de vulnerabilidad a gran escala ante eventos naturales como sismos o huracanes.

Palabras claves: factores de corrección, testigos de hormigón, resistencia a compresión del hormigón in-situ.

ABSTRACT

Evaluating concrete structures is closely linked to the accurate estimation of concrete compressive strength. Most codes require this parameter to be determined through destructive and non-destructive tests on the structure. In some cases, this estimation can be complemented with default values based on the construction period of the structure under study. In Cuba, a country with a concrete heritage spanning more than 100 years, such data is currently unavailable. For this reason, this paper aims to characterize the concrete compressive strength of existing structures in Havana using a database of over 1,960 concrete cores extracted from more than 160 buildings constructed in the city during the 20th century. The characterization is presented in terms of mean values and coefficients of variation across six periods of the 20th century. Finally, the compressive strength values were approximated using normal and log-normal probability distributions, providing valuable information for the structural assessment of individual buildings and for conducting large-scale vulnerability evaluations of the city against natural phenomena such as earthquakes and hurricanes.

Keywords: in-situ concrete compressive strength, concrete cores; corrections factors.

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1. INTRODUCTION

The structural safety analysis of reinforced concrete (RC) structures can be motivated by several reasons, as widely referenced in relevant regulations such as BS 6089:2010 [1] and BS EN 12504-1:2019 [2] as well as in the literature [3].

In general, these reasons can be grouped into two cases: 1) in new constructions, where low standard cylinder compressive strength results are obtained and 2) in existing structures, either prior to a rehabilitation process or to a change in the structure's use that increases live loads, among other factors.

Specifically in the case of existing structures (case 2), the process is complex. It involves determining the actual dimensions of the structural elements and their reinforcement, defining the true actions acting on the structure, and obtaining the mechanical strength of the materials. These are indispensable variables for performing the modeling and safety assessment of the structure, which are the final steps in evaluating its safety.

Regarding the mechanical strength of materials within the structure, it is essential to determine the concrete compressive strength (f_c). The ACI 562-19 "Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings and Commentary" [4] states that the characterization of materials within the structure, particularly the concrete in an existing structure, can initially be based on historical data. Such data establish the concrete compressive strength for different structural elements according to the time of construction, as exemplified for the United States (see Table 1).

Table 1: *Default compressive strength in concrete structures, MPa [4]*

Stage	Fottings	Beams	Slabs	Columns	Walls
1900-1919	7	14	10	10	7
1920-1949	10	14	14	14	14
1950-1969	17	21	21	21	17
1970-present	21	21	21	21	21

Additionally, several studies found in the literature in recent years address the issue of compressive strengths in existing RC structures built during different periods.

In 2000, Shimizu et al. [5] conducted a study in Japan, statistically analyzing the compressive strengths of more than 10,788 cores taken from 1,130 buildings constructed between 1926 and 1984 to determine the compressive strengths of existing structures in that country.

In 2004, Ackay [6] carried out a study in which, based on core extraction, he determined the compressive strengths of 244 buildings in Istanbul, Turkey. Similarly, Inel et al. [7] conducted a study in 2008, analyzing 1,679 cores from 167 buildings constructed between 1960 and 1998 in Turkey. That same year, Maziligüney et al. [8] processed 4,647 cores from 693 buildings built between 1940 and 2002, also in Turkey, primarily in Istanbul.

In 2009, Masi and Vona [9] analyzed the results of a campaign conducted in the Basilicata region of Italy, where more than 800 cores were extracted, and over 3,600 non-destructive tests (NDT) (using sclerometer and ultrasound) were performed on more than 200 RC buildings constructed between 1946 and 1991. Later, in 2014, Masi et al. [10] presented updated results from this campaign, which by then included 1,500 cores from approximately 300 buildings.

In 2015, Cristofaro et al. [11] presented an analysis of destructive tests (DT) and NDT on 90 buildings in the Tuscany region of Italy, constructed between the 1950s and 1980s. A total of 803 compressive strength values were analyzed, corresponding to cores extracted from the structures, as well as 3,162 NDT performed on them.

All the studies mentioned above are part of or utilize data from campaigns motivated by the need to assess the vulnerability of buildings in these regions to seismic events.

On the other hand, in 2024, S.-H. Kwon et al. [12] analyzed the concrete compressive strength of more than 600 cores from dismantled elements of existing bridges in Korea, with service lives ranging from 20 to 45 years. They applied correction factors from ACI 214.4R-10 [13] in their analysis.

In the particular case of Cuba, which has a built heritage of RC structures spanning more than 100 years, there is no information available like that referenced earlier. It is considered that having this type of information could be of great benefit for many reasons, among which we can highlight:

a) Providing data that enables large-scale vulnerability studies in the face of events such as hurricanes or earthquakes.

b) Provide designers of RC structure repair and rehabilitation projects with information that allows them to work during the conceptual ideas and preliminary design stages.

c) Provide specialists performing destructive tests (DT) and non-destructive tests (NDT) on RC structures with reference information.

To achieve this goal, this paper focuses on characterizing the compressive strengths of structural concretes used in Havana during the 20th century, utilizing a large database of concrete core compressive strengths from RC structures. The study is divided into six distinct periods, each statistically characterized by determining mean values and coefficients of variation for the concrete compressive strengths. Additionally, the Kolmogorov-Smirnov goodness-of-fit test is used to assess the fit of the data to normal and lognormal theoretical probability distributions. A previous statistical study characterizing the same database by construction period and structural element was also published by the authors in [14].

2. MATERIALS AND METHODS

2.1. Database Main Characteristics

This study was conducted by processing a database of 1,974 concrete core compressive strength values obtained from 160 RC structures built in Havana during the 20th century. These cores were extracted and tested for compression by two entities in the city: the National Company of Applied Research (ENIA) and the Center for Research and Development of Construction (CIDC), between 1998 and 2017. Table 2 summarizes the distribution of the cores in the database by structural element.

Table 2: Cores database distribution according to structural element type

Structural element	Number of cores	Percentage (%)
Column	354	17,9
Slab	899	45,4
Wall	40	2,0
Beam	333	16,9
Footing	348	17,6
Total	1974	100

2.2. Values Correction

Each concrete core compressive strength (f_{test}) was corrected applying the correction factors proposed by Fernández and Howland (A Fernández Domínguez & Albear, 2017), resulting in the same number of corrected concrete core compressive strength values ($f_{test, corr}$) (1).

$$f_{test,corr} = F_{h/d} * F_{dir} * F_{dañ} * F_{a} * f_{test} \quad (1)$$

Where:

$F_{h/d}$ is the correction factor associated with the slenderness of the core

F_{dir} is the correction factor associated with the extraction direction of the core

$F_{dañ}$ is the correction factor associated with the damage suffered by the core during the extraction process

F_{a} is the factor associated with the presence of reinforcing steel bars embedded in the core

2.3. Database Depuration

The next step in the process was depurating the database. First, following the criteria of ACI 214.4R-10(16) [13] in its appendix A.2, the $f_{test, corr}$ values on each building where grouped by structural element type, and a student t-test was performed determine whether these batches (group of cores) could all be considered representative of the same population. In 17 of the 160 RC structures, the batches were found to be different with a 95% confidence level, resulting in a total of 177 batches.

Next, each of these batches underwent an outlier identification process following the recommendations of ASTM E 178-21 [15]. After applying a two-sided test with a 5% significance level to the 177 batches, 9 batches were found to contain one or two outlier values, totaling 14 outliers. After removing these $f_{test, corr}$ values, the database was reduced to 1960 cores. All the details of depuration process presented in this paper can be found in [16].

3. RESULSTS AND DISCUSION

The average compressive strength ($f_{cm,is}$), standard deviation (S) and coefficient of variation (CV) were determined on each of the 177 identified batches using equations 2,3 and 4 respectively. Figures 1 and 2 show the values of $f_{cm,is}$ and CV of each of the 177 batches, plotted against their approximate year of construction. In both graphs, second-degree polynomial trend lines are included to describe the trend in the quality of the concretes over time, despite the significant scatter in the data. As shown in fig. 1, the $f_{cm,is}$ exhibits an upward trend as the century progresses, with a slight decline toward the end. Conversely, and in complete agreement, the CV decreases as the century progresses but increases again toward the end.

$$f_{cm,is} = \frac{1}{n}\sum_{i=1}^{n} f_{test,corr} \quad (2)$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{\left(f_{test,corr} - f_{cm,is}\right)^2}{(n-1)}} \quad (3)$$

$$CV = {f_{cm,is}}/{S} \quad (4)$$

Where:

n: is the number of $f_{test,corr}$ values of each batch.

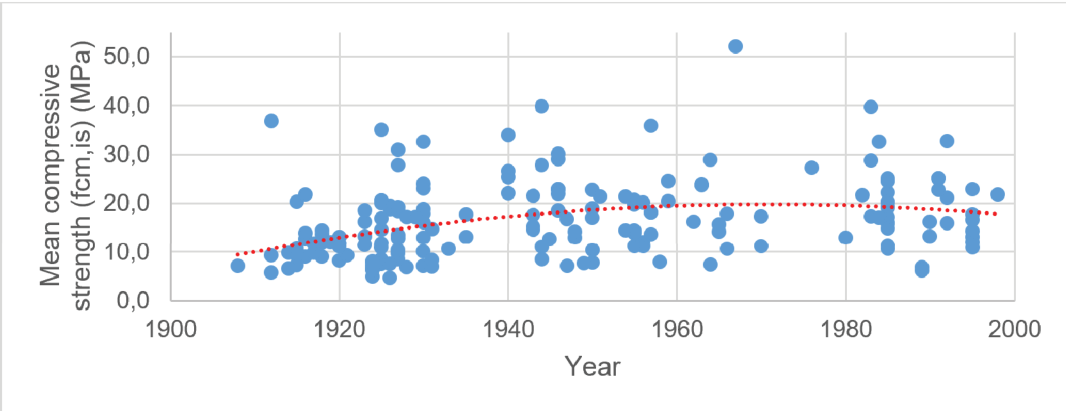

Figure 1: *Mean compressive strength values (fcm,is) vs. construction year for each batch.*

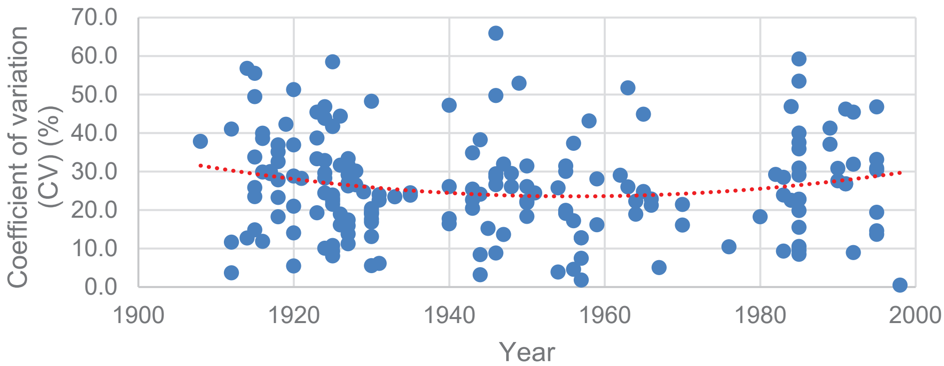

Figure 2: *Coefficient of variation (CV) vs. construction year for each batch*

To perform a more precise characterization of throughout the 20th century, the century was divided into six periods based on historical, technical, and economic studies, the details of which are provided in [16]. The graphs in Figure 3 reflect the main statistical parameters for each period. As shown in fig 3.c, the mean values of $f_{cm,is}$ remained relatively stable from the 1930s onward, without exceeding 20 MPa. Regarding the CV (fig 3.d) a similar pattern is observed, with values oscillating between 24.5% and 27.7% starting from 1945. The first period shows a logical behavior, with the highest value of CV coinciding with the lowest value of $f_{cm,is}$. All these parameters, including the confidence intervals for $f_{cm,is}$ and CV determined at a 95% confidence level, are presented in Table 3.

In figure 4, the frequency distributions (histograms) of $f_{cm,is}$ for each period are shown alongside the theoretical distributions (normal and log-normal). To determine how well these distributions fit the data, the Kolmogorov-Smirlnov (K-S) goodness-of-fit test was applied. The P-values for each period are shown also in Table 4. As can be observed, in four of the six periods, the $f_{cm,is}$ values exhibited a better fit to the log-normal distribution (P-values close to 1). According to ACI 214.4-10(16) [13] this behavior is typical of concrete with low quality control. This finding aligns with the characteristics of each study period, as detailed in [16].

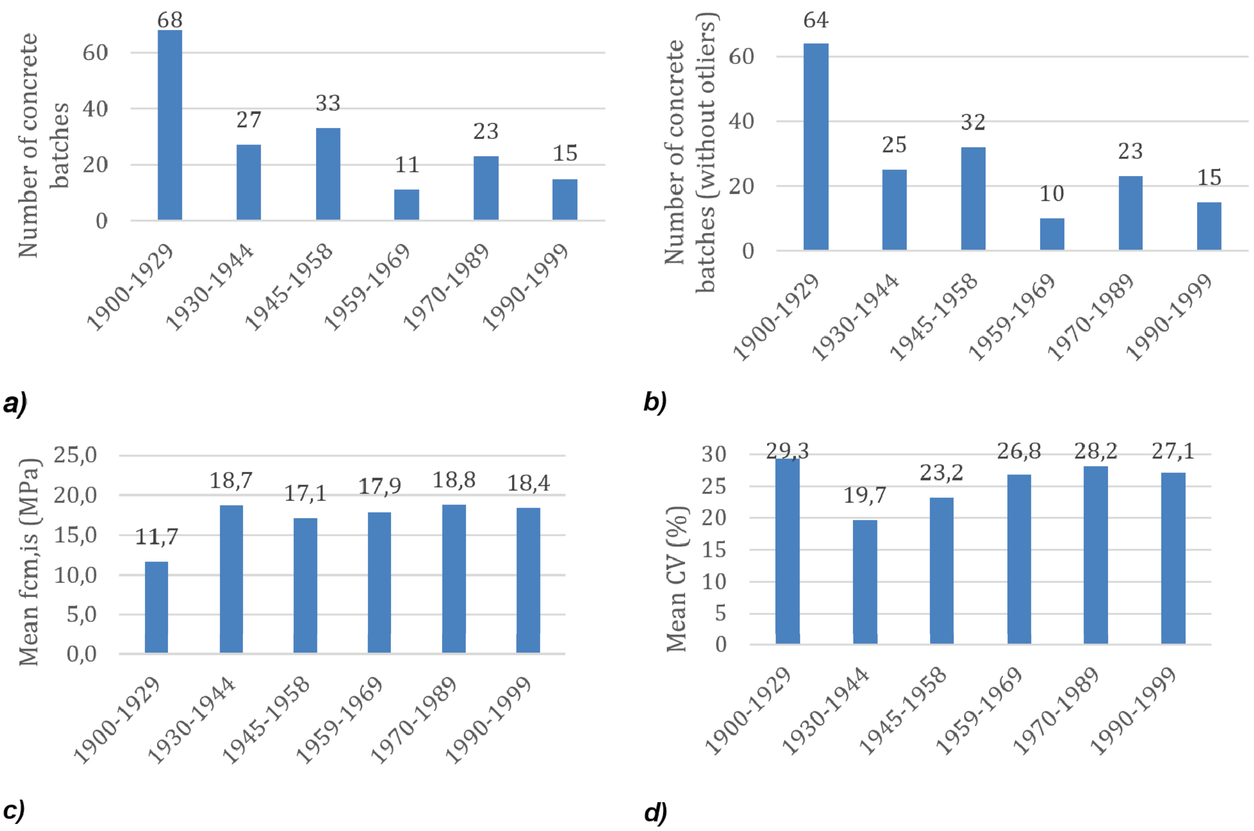

Figure 3: *Main statistical parameters of the database for the six periods identified: a) number of concrete batches b) number of concrete batches (without outliers) c) Mean fcm,is d) Mean CV*

Table 3: Main statistical parameters of concrete strength by construction period.

Construction period	Number of batches	Mean $f_{cm,is}$ (MPa)	Mean $f_{cm,is}$ Confidence interval (MPa)	Mean CV (%)	Mean CV Confidence interval
1900-1929	68	11,7	[10,57; 12,77]	29,3	[26,17; 32,48]
1930-1944	27	18,7	[15,15; 22,29]	19,7	[16,30; 23,07]
1945-1958	33	17,1	[14,68; 19,59]	23,2	[18,76; 27,64]
1959-1969	11	17,9	[13,21; 22,63]	26,8	[20,23; 33,39]
1970-1989	23	18,8	[15,39; 22,26]	28,2	[22,25; 34,17]
1990-1999	15	18,4	[15,12; 21,67]	27,1	[19,50; 34,67]
Total	**177**				

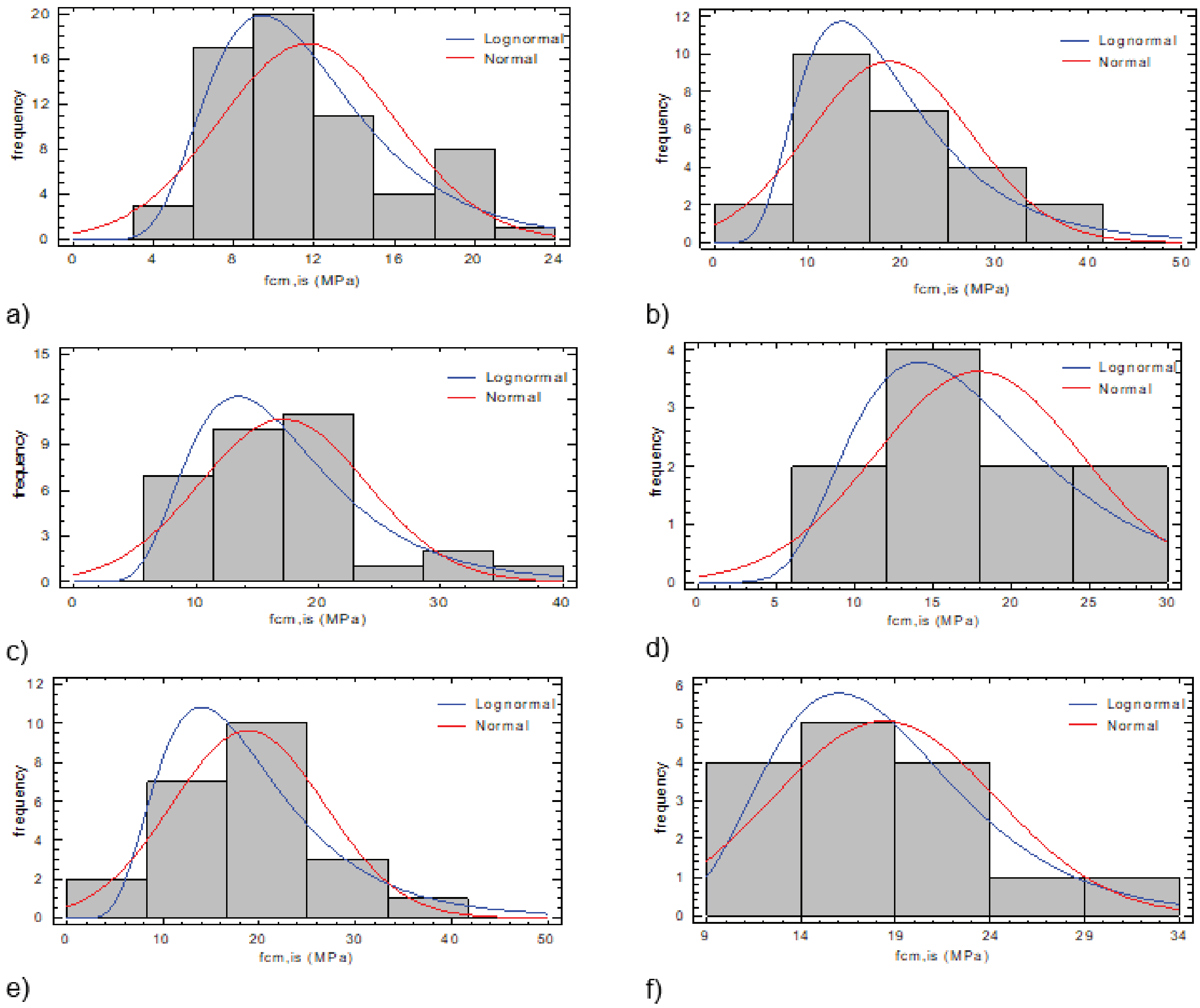

Figure 4: *Frequency distributions of concrete strength for each construction period: a) 1900-1929, b) 1930-1944, c) 1945-1958, d) 1959-1969, e) 1970-1989, f) 1990-1999.*

Table 4*: P-values and parameters of the normal and log-normal distributions for each period*

	Construction period					
	1900-1929		1930-1944		1945-1958	
Distributions	**Normal**	**Lognormal**	**Normal**	**Lognormal**	**Normal**	**Lognormal**
P-value (K-S test)	0,600	0,973	0,692	0,9999	0,703	0,930
μ	11,677	*11,704*	18,720	18,851	17,138	17,237
σ	4,407	4,616	8,650	9,330	6,822	7,396

Table 4: P-values and parameters of the normal and log-normal distributions for each period (continuation)

	Construction period					
	1959-1969		1970-1989		1990-1999	
Distributions	**Normal**	**Lognormal**	**Normal**	**Lognormal**	**Normal**	**Lognormal**
P-value (K-S test)	0,9997	0,989	0,968	0,879	0,902	0,978
μ	17,920	18,193	18,826	19,058	18,4	18,441
σ	6,586	7,828	7,939	9,151	5,917	5,826

4. CONCLUSIONS

The results achieved in this work provide highly useful information for the future evaluation of reinforced concrete buildings in Havana. For individual cases, the average values of $f_{cm, is}$ and CV for each studied period, as provided in this paper, can serve as fundamental references. For large-scale vulnerability assessments in Havana, in addition to the aforementioned values, the parameters associated with the normal and log-normal distributions (whichever provides the best fit in each case) will be particularly valuable. Expanding the database used for this study, as well as potentially redefining the periods outlined in it, could further enhance the results of this investigation.

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REFERENCES

[1] *BS 6089:2010. Assessment of in-situ compressive strength in structures and precast concrete components. Complementary guidance to that given in BS EN 13791*, B. Standard, 2010. [Online]. Available: https://www.bsigroup.com/en-GB/products-and-services/standards/

[2] *BS EN 12504-1:2019. Testing concrete in structures - Cored specimens. Taking, examining and testing in compression*, B. Standard, 2020. [Online]. Available: https://www.bsigroup.com/en-GB/products-and-services/standards/

[3] D. Couto, M. Carvalho, A. Cintra, and P. Helene, "Estruturas de concreto. Contribuição à análise da segurança em estruturas existentes," *Revista IBRACON de Estruturas e Materiais,* vol. 8, pp. 365-389, 2015, doi: https://doi.org/10.1590/S1983-41952015000300007.

[4] *ACI 562-19: Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures and Commentary*, A. C. I. ACI, 38800 Country Club Drive, Farmington Hills, M, 2019. [Online]. Available: https://www.concrete.org/store/productdetail.aspx?ItemID=562U19&Format=PROTECTED_PDF&Language=English&Units=US_Units

[5] Y. Shimizu, M. Hirosawa, and J. Zhou, "Statistical analysis of concrete strength in existing reinforced concrete buildings in Japan," in *12th World conference on earthquake engineering, Auckland, New Zealand*, 2000. [Online]. Available: https://iitk.ac.in/nicee/wcee/article/1499.pdf. [Online].

[6] B. Akcay, "Variation of in-place concrete core strength in structures from Istanbul area: Statistical analysis of concrete core data," *Journal of materials in civil engineering,* vol. 16, no. 5, pp. 507-510, 2004, doi: https://doi.org/10.1061/(ASCE)0899-1561(2004)16:5(507).

[7] M. Inel, S. Senel, and H. Un, "Experimental evaluation of concrete strength in existing buildings," *Magazine of Concrete Research,* vol. 60, no. 4, pp. 279-289, 2008, doi: https://doi.org/10.1680/macr.2007.00091.

[8] L. Mazılıgüney, F. Azılı, and İ. Yaman, "In-situ concrete compressive strength of residential, public and military structures," in *Proc., 8th Int. Congress on Advances in Civil Engineering*, 2008. [Online]. Available: https://www.academia.edu/download/34454900/PAPER-ACE2008.pdf.

[9] A. Masi and M. Vona, "Estimation of the in-situ concrete strength: provisions of the European and Italian seismic codes and possible improvements," in *Eurocode*, 2009, vol. 8, pp. 67-77. [Online]. Available: https://www.reluis.it/images/pubblicazioni/2/978-88-89972-16-8.pdf#page=76.

[10] A. Masi, A. Digrisolo, and G. Santarsiero, "Concrete strength variability in Italian RC buildings: analysis of a large database of core tests," *Applied mechanics and materials,* vol. 597, pp. 283-290, 2014, doi: https://doi.org/10.4028/www.scientific.net/AMM.597.283.

[11] M. T. Cristofaro, R. Pucinotti, M. Tanganelli, and M. De Stefano, "The dispersion of concrete compressive strength of existing buildings," *Computational Methods, Seismic Protection, Hybrid Testing and Resilience in Earthquake Engineering: A Tribute to the Research Contributions of Prof. Andrei Reinhorn,* pp. 275-285, 2015, doi: https://doi.org/10.1007/978-3-319-06394-2_16.

[12] S.-H. Kwon, J.-S. Lee, and H.-K. Kim, "On determination protocols of characteristic in-situ compressive strength of concrete for existing structure: Case study with core samples from actual bridges," *Case Studies in Construction Materials,* vol. 20, p. e03031, 2024, doi: https://doi.org/10.1016/j.cscm.2024.e03031.

[13] *ACI 214.4R-10(16): Guide for obtaining Cores and Interpreting Compressive Strength Results*, A. C. I. ACI, 38800 Country Club Drive, Farmington Hills, MI 48331, U.S.A, 6/1/2010 2010. [Online]. Available: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51663805

[14] A. F. Domínguez, J. J. H. Albear, and A. M. del Castillo Serpa, "Resistencias mecánicas de los hormigones estructurales in-situ empleados en edificaciones de la habana en el siglo XX," presented at the XIX Convención Científica de Ingeniería y Arquitectura, 2018. [Online]. Available: https://www.researchgate.net/publication/329191339.

[15] *ASTM E178-21 Standard Practice for Dealing With Outlying Observations*, A. S. f. t. M. ASTM, 2021. [Online]. Available: https://www.astm.org/e0178-21.html

[16] A. F. Domínguez, "Caracterización de las resistencias mecánicas de los hormigones estructurales empleados en edificaciones de La Habana en el siglo XX," Master, Technological University of Havana, CUJAE, 2018. [Online]. Available: https://www.researchgate.net/publication/329403545_CARACTERIZACION_DE_LAS_RESISTENCIAS_MECANICAS_DE_LOS_HORMIGONES_ESTRUCTURALES_EMPLEADOS_EN_EDIFICACIONES_DE_LA_HABANA_EN_EL_SIGLO_XX