STUDY OF THE FREQUENCY RESPONSE OF CONCRETE SPECIMENS IN DIFFERENT STRENGTH CLASSES

ESTUDO DA RESPOSTA EM FREQUÊNCIA DE CORPOS DE PROVA DE CONCRETO EM DIFERENTES CLASSES DE RESISTÊNCIA

ESTUDIO DE LA RESPUESTA EN FRECUENCIA DE MUESTRAS DE HORMIGÓN EN DIFERENTES CLASES DE RESISTENCIA

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ABSTRACT

Concrete, being a heterogeneous composite material sensitive to the proportions of its constituents, exhibits significant variations in its mechanical and dynamic behavior. This study analyzed the vibrational behavior of concrete specimens with four compressive strength classes (15, 20, 25, and 30 MPa) through experimental modal analysis and determination of Frequency Response Functions (FRF). For each class, 10 specimens were molded in plywood forms using Portland cement CP II, quartz sand, granite aggregate, and water in specific volumetric proportions, followed by curing for 28 days. Impulsive excitation was applied with an instrumented hammer, and acceleration responses were acquired using a dedicated acquisition system in the 0 to 2560 Hz range, with evaluation of the coherence between excitation and response for FRF validation. The curves obtained showed a systematic shift of resonance peaks to higher frequencies as compressive strength increases, in addition to more sTable spectral responses in the higher classes, highlighting the strong correlation between dynamic stiffness and mechanical strength. The methodology employed confirmed the potential of modal analysis as a sensitive non-destructive technique for characterizing the vibrational response of concrete, providing relevant information for applications in quality control and evaluation of structures subjected to dynamic actions.

Keywords: Frequency Response. Experimental Modal Analysis. Concrete. Dynamic Properties. Strength Classes.

RESUMO

O concreto, por ser um material compósito heterogêneo e sensível às proporções de seus constituintes, apresenta variações significativas em seu comportamento mecânico e dinâmico. Este estudo analisou o comportamento vibracional de corpos de prova de concreto com quatro classes de resistência à compressão (15, 20, 25 e 30 MPa) por meio de análise modal experimental e determinação das Funções de Resposta em Frequência (FRF). Para cada classe foram moldados 10 corpos de prova em formas de madeirite, utilizando cimento Portland CP II, areia quartzosa, brita granítica e água em proporções volumétricas específicas, seguidos de cura por 28 dias. A excitação impulsiva foi aplicada com martelo instrumentado, e as respostas de aceleração foram adquiridas em sistema de aquisição dedicado, na faixa de 0 a 2560 Hz, com avaliação da coerência entre excitação e resposta para validação das FRF. As curvas obtidas mostraram deslocamento sistemático dos picos

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de ressonância para frequências mais elevadas à medida que a resistência à compressão aumenta, além de respostas espectrais mais estáveis nas classes superiores, evidenciando a forte correlação entre rigidez dinâmica e resistência mecânica. A metodologia empregada confirmou o potencial da análise modal como técnica não destrutiva sensível para caracterização da resposta vibracional do concreto, fornecendo subsídios relevantes para aplicações em controle de qualidade e avaliação de estruturas sujeitas a ações dinâmicas.

Palavras-chave: Resposta em Frequência. Análise Modal Experimental. Concreto. Propriedades Dinâmicas. Classes de Resistência.

RESUMEN
El hormigón, al ser un material compuesto heterogéneo sensible a las proporciones de sus componentes, presenta variaciones significativas en su comportamiento mecánico y dinámico. Este estudio analizó el comportamiento vibracional de probetas de hormigón con cuatro clases de resistencia a la compresión (15, 20, 25 y 30 MPa) mediante análisis modal experimental y la determinación de las Funciones de Respuesta en Frecuencia (FRF). Para cada clase, se moldearon 10 probetas en encofrados de madera contrachapada utilizando cemento Portland CP II, arena de cuarzo, árido granítico y agua en proporciones volumétricas específicas, tras lo cual se dejó curar durante 28 días. Se aplicó excitación impulsiva con un martillo instrumentado y se adquirieron las respuestas de aceleración mediante un sistema de adquisición específico en el rango de 0 a 2560 Hz, evaluando la coherencia entre la excitación y la respuesta para la validación de la FRF. Las curvas obtenidas mostraron un desplazamiento sistemático de los picos de resonancia a frecuencias más altas a medida que aumenta la resistencia a la compresión, además de respuestas espectrales más esTables en las clases más altas, lo que destaca la fuerte correlación entre la rigidez dinámica y la resistencia mecánica. La metodología empleada confirmó el potencial del análisis modal como técnica sensible y no destructiva para caracterizar la respuesta vibracional del hormigón, proporcionando información relevante para aplicaciones en el control de calidad y la evaluación de estructuras sometidas a acciones dinámicas.

Palabras clave: Respuesta en Frecuencia. Análisis Modal Experimental. Hormigón. Propiedades Dinámicas. Clases de Resistencia.

1 INTRODUCTION

Concrete is one of the most widely used structural materials in the world due to its versatility, durability, and ease of molding. Its application is widely disseminated in infrastructure works, buildings, paving and precast elements. However, as it is a heterogeneous composite material, its mechanical and dynamic response depends directly on the composition, the proportion of the aggregates, the quality of the cement pulp, and the curing process (SEGALIN et al., 2020). Among its fundamental properties, compressive strength is the most used for structural classification and design, serving as a reference for the overall performance of the material (NEGRI et al., 2024). However, properties related to dynamic behavior, such as natural frequencies, vibration modes, and damping, also play a significant role in situations where concrete is subject to dynamic actions, such as traffic, wind, industrial vibrations, and impacts.

Experimental modal analysis (AME) is a well-established technique for the characterization of the dynamic properties of materials and structural systems. It allows the determination of natural frequencies, vibration modes, and damping factors from data obtained through mechanical excitation and response measured by appropriate sensors (Rosa et al., 2016). The Frequency Response Function (FRF), which relates the structural response to an applied excitation, is one of the main tools in the identification of these properties. For cementitious materials, FRF has been used to assess structural integrity, identify damage, investigate stiffness differentiations, and understand how variations in concrete composition influence its dynamic behavior (MAGALHÃES et al., 2024).

The heterogeneity of concrete implies that small changes in the proportion of aggregates, water content, type of cement or additives can significantly modify its overall stiffness, directly reflecting on the vibrational response. Studies show that lower strength concretes have lower natural frequencies due to their lower stiffness, while higher strength concretes tend to exhibit vibration modes in higher ranges (ALMEIDA et al., 2012). This relationship between mechanical strength and dynamic behavior is fundamental, especially in non-destructive techniques, where the frequency response allows inferring internal properties without causing damage to the material.

In addition, the application of dynamic methods for the evaluation of cementitious materials has gained relevance in the context of *Structural Health Monitoring* (SHM). Techniques based on modal analysis allow the identification of subtle variations in the internal structure of materials, being able to detect early damage, microcracking, or progressive

degradation (HU et al., 2018). Within this scope, the study of FRFs of specimens with different resistance classes provides important subsidies to understand how dynamic properties are affected by variations in the dosing process and how such information can be used in the monitoring of real structural elements.

The use of dynamic testing is also encouraged by its non-destructive nature and high sensitivity to stiffness variations. While destructive tests evaluate the final properties of the material, such as compressive strength, modal analysis allows the observation of changes from the initial states of damage, making it a promising technique for monitoring throughout the useful life of the structure. Thus, understanding how different strength classes respond in dynamic terms contributes not only to academic purposes, but to practical applications in technological control, structural inspections, and the development of concretes with specific dynamic performance.

In the experimental context, obtaining FRF from impulsive excitation has significant advantages, such as operational simplicity, speed of execution, and good repeatability for small specimens. Allied to this, the advancement of computational tools such as MATLAB facilitates the processing, visualization and interpretation of vibrational data. The generation of three-dimensional graphs (frequency × magnitude × sample) allows you to identify consistent patterns between resistance classes, facilitating the visualization of typical differences in stiffness and dynamic behavior.

Given this scenario, it is relevant to understand how different resistance classes influence the frequency response of concrete. Systematic analysis of these responses provides valuable insights into the relationship between mechanical and vibrational properties, allowing for a more comprehensive characterization of the material. Thus, this study contributes to the understanding of the dynamic behavior of concrete as a function of its strength, offering a robust experimental approach that can serve as a basis for future research in structural engineering, integrity monitoring and non-destructive methods applied to cementitious materials.

2 METHODOLOGY

The methodology adopted in this study was structured to allow the dynamic characterization of concrete specimens with different classes of compressive strength, using experimental methods of modal analysis and computational processing of the signals obtained. The procedure ranged from the molding and curing of the samples to the acquisition

of data by impulsive excitation and the analysis of the FRF. The steps were performed in a standardized manner to ensure reproducibility and comparability between classes.

2.1 MOLDING OF THE SPECIMENS

The production of the specimens followed a strict protocol of molding and material control, with the objective of ensuring experimental repeatability and reducing external variables that could influence the dynamic behavior. The samples were molded in previously sanded plywood molds, cleaned and covered with commercial release agent (Vedacit®), ensuring adequate surface finish conditions and facilitating the demolding process.

Specimens belonging to the four strength classes conventionally used in structural concrete works were manufactured: 15 MPa, 20 MPa, 25 MPa and 30 MPa, totaling 10 specimens for each class, which provides sufficient statistical basis for dynamic behavior analysis.

The concrete was prepared using Portland cement composite CP II, of the CAUÊ® brand, whose chemical composition, provided by the manufacturer and presented in Table 1, consists essentially of tricalcium silicate, dicalcium silicate, calcium aluminates and ferro-aluminates, gypsum and standardized mineral additions. This characterization is fundamental, because cement mineralogy is directly related to hydration processes, the development of stiffness and, consequently, the vibrational properties of the material.

Table 1

Chemical composition of the Portland cement of class CPII used in the samples

Component	Concentration Range (%)
Tricalcium silicate	20-70
Dicalcium silicate	10-60
Calcium ferroaluminate	5-15
Calcium Sulfate	2-8
Tricalcium Aluminate	1-15
Calcium carbonate	0-10
Magnesium oxide (free)	0-6
Calcium oxide (free)	0-3

Source: From the author (2025)

The volumetric proportions of cement, quartz sand, granitic gravel and water were defined as shown in Table 2, adjusted to meet the expected resistance classes. The homogenization of the materials was carried out manually in a rigid container of 0.001 m³,

starting with the mixing of the dry components, followed by the gradual addition of water to obtain a consistency suiTable for molding.

Table 2

Proportions of concrete components for compressive strength classes equivalent to 15, 20, 25 and 30MPa

Resistance Class (MPa)	Cement (m³)	Sand (m³)	Crushed stone (m³)	Water (m³)
15 MPa	0,0010	0,0025	0,0040	0,0020
20 MPa	0,0010	0,0028	0,0035	0,0023
25 MPa	0,0015	0,0023	0,0025	0,0020
30 MPa	0,0015	0,0020	0,0020	0,0020

Source: From the author (2025)

After mixing, the concrete was placed in the forms in two successive layers, each submitted to 12 blows of compaction with a metal rod, according to the classic recommendation for eliminating bubbles and obtaining good density. The final dimensions of the specimens were standardized at 0.03 m × 0.06 m × 0.40 m, which reduces variability in the moment of inertia and ensures comparability between samples.

The curing process was conducted in a protected environment for 28 days, respecting the conventional criteria for stabilization of mechanical resistance. After this period, the specimens were demolded, identified and visually inspected to confirm their physical integrity.

2.2 EXPERIMENTAL SETUP AND INSTRUMENTATION

The dynamic characterization was performed by experimental modal analysis with impulsive excitation, a widely used technique to identify the vibrational properties of systems with simple geometry and heterogeneous materials. To minimize support interference and allow the specimen to vibrate freely, each specimen was suspended by nylon wires fixed near the ends—a configuration equivalent to the "free–free" boundary conditions often employed for determining natural frequencies in test elements.

Mechanical excitation was performed with a PCB *Piezotronics* instrumented hammer model 086C03, equipped with a metal tip (sensitivity 2.417 mV/N). Vibration response was measured by a Piezotronics PCB piezoelectric accelerometer model 352C33, with a sensitivity of 98.5 mV/g, fixed at 0.06 m from the end for efficient capture of longitudinal and flexional modes.

The choice of excitation position (0.06 m from the end) and accelerometer position was set in such a way as to maximize the energy transferred to the system and allow clear identification of resonance peaks, reducing nodal effects that could impair the reading of certain modes. For each specimen, five successive impacts were performed, allowing the average of the signals to reduce random noise and increase the robustness of the obtained spectra. Between each impact, the vibration was fully dampened, avoiding overlapping transients.

2.3 SIGNAL ACQUISITION AND DIGITAL PROCESSING

The excitation and response signals were recorded by a *National Instruments* (NI) acquisition system consisting of: NI cDAQ-9174 chassis, NI 9234 dynamic acquisition modules (8 channels), and LabVIEW software, with the *Sound and Vibration library.*

The system was configured to acquire the signal in the range of 0–2560 Hz, with spectral resolution of 0.5 Hz, sufficient value to identify dominant modes and characterize the dynamics of small elements.

During the tests, the coherence between the force and acceleration signals was continuously analyzed. Assays with coherence less than 0.95 were discarded and repeated, ensuring the reliability of the spectra and the representativeness of the FRF. The determination of FRFs was performed directly in *LabVIEW* by means of the ratio between the response and excitation Fourier spectra. The processed data were exported for complementary analysis and graphical organization.

2.4 DETERMINATION AND ANALYSIS OF FREQUENCY RESPONSE FUNCTIONS (FRF)

The identification of FRF was the central step in the dynamic characterization of the specimens, allowing to quantify the relationship between the applied force and the resulting vibratory response. The FRF was obtained directly from the signals acquired by the instrumentation system, using the spectral ratio between the Fast Fourier Transform (FFT) of the acceleration and the FFT of the impact force, a procedure widely consolidated in the literature of experimental modal analysis.

The *free–free* configuration, achieved by suspending the specimens by nylon wires, provided virtually free boundary conditions, eliminating rigid constraints that could mask or displace the material's intrinsic natural frequencies. This condition favors the excitation of a

broad spectrum of vibratory modes, allowing the FRF to reveal both longitudinal and flexional modes, depending on the intensity and location of the impact.

The acquired signals were previously filtered and inspected for spectral coherence, a parameter that expresses the quality of the relationship between excitation and response. Only FRFs from impacts with coherence values close to 1.0 were considered valid, ensuring that the spectrum faithfully represented the dynamic behavior of the sample. Impacts with reduced coherence, potentially associated with environmental noise, clamping slippage or off-axis excitations, were automatically ruled out and repeated.

Once validated, the FRFs exhibited well-defined magnitude peaks, associated with the dominant natural frequencies of each specimen. These peaks represent resonance conditions, in which the energy introduced by the impact coincides with the vibration frequencies of the concrete element. The clarity of these peaks, observed even in the lower resistance classes, reflects the appropriate combination of instrumentation, repetition of the tests and geometric uniformity of the specimens.

In addition to the direct identification of natural frequencies, FRF allowed the observation of complementary characteristics of vibratory behavior, such as:

- relative amplitude of responses, associated with the dissipation capacity and rigidity of the system;
- spectral separation between classes, indicating differences in global stiffness induced by variation in mechanical strength;
- presence of secondary modes, which appear more intensely in less rigid materials;
- stability of the peaks between replications, evidencing reproducibility and sensitivity of the methodology.

The use of five consecutive impacts and subsequent spectral mean was fundamental to eliminate specific irregularities and highlight only the systematic dynamic components. This procedure resulted in smooth spectral curves, with a high signal-to-noise ratio and excellent definition of the resonance regions.

The consolidated FRFs unequivocally demonstrated that the concrete grades exhibit distinct vibrational signatures. Concretes of higher strength showed displacement of the main peaks to higher frequency ranges, reflecting greater dynamic stiffness, while concretes of lower resistance showed lower peaks and, in general, a greater number of modes within the analyzed range.

In summary, the FRF determination process adopted in this study:

- ensured high accuracy in identifying natural frequencies,
- showed robustness in the face of the intrinsic variabilities of the material,
- allowed direct comparison between classes,
- and provided solid bases for the interpretation of the vibrational differences between the types of concrete analyzed.

The final result is a set of sTable, consistent and adequate FRFs for comparative analyses between resistance classes, an essential condition for the objectives of this study.

3 RESULTS AND DISCUSSION

The modal analysis performed by means of impulsive excitation allowed to obtain the Frequency Response Functions (FRF) of the concrete specimens referring to the four strength classes studied (15, 20, 25 and 30 MPa). The extracted FRFs directly reflect the vibrational behavior of each sample and make it possible to identify the predominant natural frequencies. As the experimental procedure has been standardized for all specimens, the observed differences in natural frequencies can be attributed to the intrinsic properties of each grade of concrete.

From the average of the signals obtained in five consecutive impacts, it was possible to reduce any occasional fluctuations and ensure statistical stability to the results. This procedure ensured that the FRF curves faithfully represented the dynamic behavior of the samples, highlighting the resonance frequencies clearly and consistently. The frequency by magnitude graphs, shown in Figure 1, show the curves of the four classes of concrete, showing clear differences between the materials.

Figure 1

Frequency graphs by magnitude of the dynamic responses of the specimens: (a) 15MPa (b) 20MPa (c) 25MPa (d) 30MPa
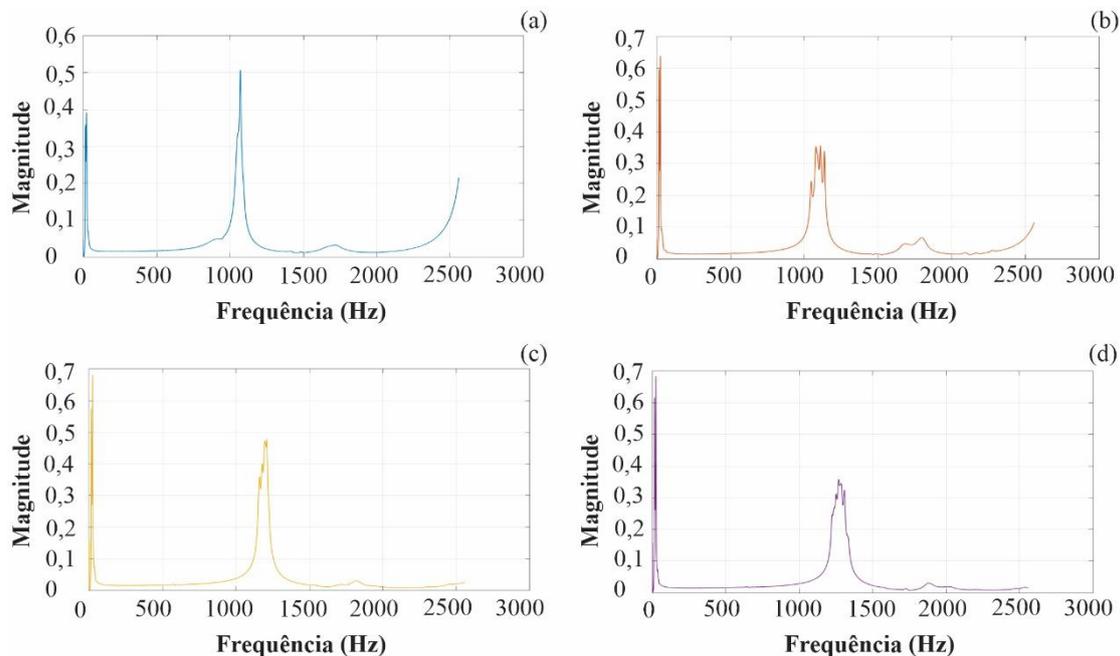
Source: From the author (2025)

In the 15 MPa samples (Figure 1a), the presence of two well-defined peaks is observed, one around 1,000 Hz and the other close to 1,500 Hz, both with high magnitudes, indicating lower rigidity and greater dynamic mobility. As the resistance class increases, FRFs start to show shifted peaks to higher frequencies and, in general, with greater sharpness and lower spectral dispersion. The 20 MPa (Figure 1b) and 25 MPa (Figure 1c) concretes show this progressive displacement, with the first peak remaining in lower ranges, but the main peak migrating to higher regions of the analyzed range. In 30 MPa concrete (Figure 1d), this trend is even more evident, with the dominant peak concentrated in a higher frequency region compared to 15 MPa concrete. This behavior confirms the direct relationship between material stiffness and increased compressive strength, reflected in the upward shift of natural frequencies.

Another relevant aspect identified in the FRFs obtained is the variation in the number and definition of the vibratory modes along the analyzed range. The 15 MPa concrete presents a more "spread" response, with multiple undulations before and after the main peaks, evidencing greater flexibility and the presence of several modes of lower energy. In the higher classes, especially 25 MPa and 30 MPa, the curves become more concentrated and clean, with fewer secondary peaks and modes distributed predominantly in higher

ranges. This suggests that, in addition to increasing overall rigidity, increasing resistance reduces excitation from lower modes, resulting in more rigid vibrational behavior and more sTable spectra. These patterns corroborate the direct influence of mechanical strength on the dynamics of concrete.

The superimposition of the curves in a single graph, presented in Figure 2, allows us to directly visualize the spectral separation between the resistance classes. A progressive shift of the main peaks to higher frequency regions is observed as the resistance increases, in addition to a reduction in secondary undulations and greater definition of the peaks in the higher classes. This integrated visualization clearly shows the correlation between dynamic stiffness and compressive strength, reinforcing the consistency of the results obtained.

Figure 2

Frequency graphs by magnitude of the dynamic responses of the specimens: (a) 15MPa (b) 20MPa (c) 25MPa (d) 30MPa
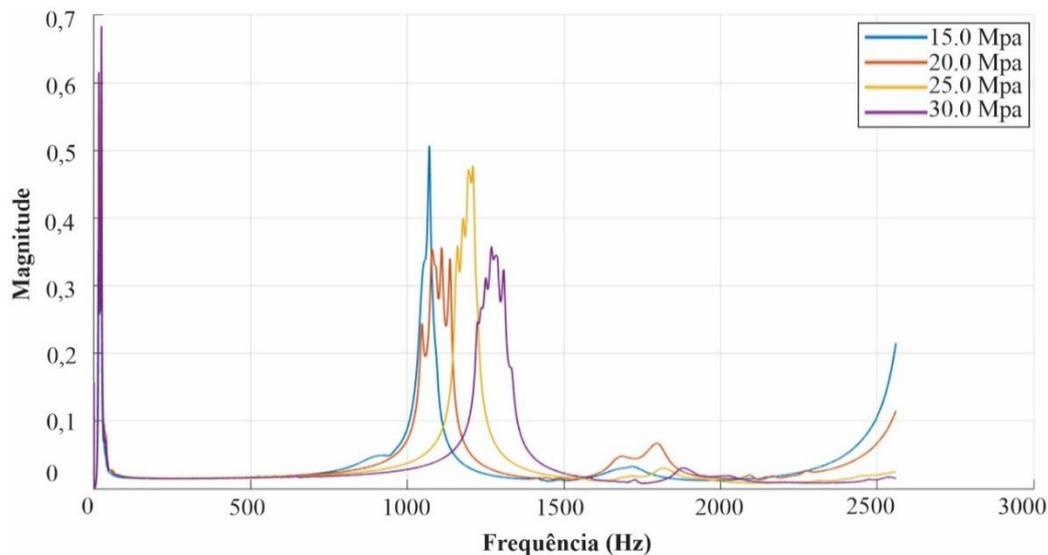
Source: From the author (2025)

The trend observed in this study is in line with recent findings in the literature in modal analysis applied to cementitious materials. Research such as that of Silva et al. (2025) demonstrates that variations in the composition of concrete, whether in the cementitious matrix, aggregates or additives, result in significant differences in natural frequencies and damping. These studies reinforce that the vibrational behavior is highly sensitive to the overall stiffness of the sample, corresponding to what was observed in the specimens tested in this work.

Other authors also highlight the potential of modal analysis for dynamic characterization of concrete structural elements. Beskhyroun et al., (2020), for example, applied similar techniques to evaluate the dynamic behavior of a reinforced concrete building, verifying that the identification of natural frequencies is capable of evidencing differences related to geometric variations, stiffness, or the presence of damage. These studies corroborate the use of frequency response as a reliable tool to investigate the dynamic performance of cementitious systems.

Modal analysis has also been used to identify subtle structural changes, even in apparently intact elements. Recent studies, such as those by Sartorti et al. (2024), show that small modifications in the state of the structure, such as initial cracking or changes in boundary conditions, can result in detecTable changes in natural frequencies or modal shapes. These findings reinforce the sensitivity of the method, which could also be observed in this study, where modest differences between resistance classes were sufficient to generate very distinct FRF curves.

The results obtained demonstrate the potential of modal analysis to differentiate concretes with distinct mechanical properties. The clear separation between the classes, observed from the FRFs, suggests that the dynamic parameters can serve as reliable indicators of the stiffness and, consequently, the mechanical strength of the specimens. This behavior reinforces the applicability of dynamic tests as a non-destructive alternative for concrete characterization.

In summary, the results show that:

- lower strength concretes have lower natural frequencies and a greater number of modes in the analyzed range;
- stronger concretes exhibit concentrated response at higher frequencies, reflecting greater stiffness;
- the FRF curves allow clear and visual distinction between the classes studied;
- Modal analysis is adequate and sensitive to evaluate the mechanical properties of concrete without destructive testing.

These results validate the effectiveness of the methodology employed and reinforce the potential of the study for future applications related to both structural monitoring and technological control of cementitious materials.

4 CONCLUSION

The experimental modal analysis performed in this study allowed to consistently characterize the dynamic behavior of concrete specimens belonging to four distinct classes of compressive strength. From the FRF, it was possible to clearly identify the natural frequencies of each sample and understand how these responses change as a function of the stiffness and mechanical properties associated with the resistance class.

The results showed that concretes of lower strength, such as those of 15 MPa, have natural frequencies located in lower ranges and greater sensitivity to spectral variations, reflecting reduced structural stiffness. With the increase in compressive strength, a systematic displacement of the main peaks to higher frequency regions was observed, accompanied by more sTable and well-defined FRF curves, a typical behavior of materials with higher dynamic stiffness. This trend was consistently verified among the classes, evidencing the ability of modal analysis to distinguish concretes with different levels of resistance.

The methodology adopted, encompassing standardized production of the specimens, controlled curing, impulsive excitation and judicious processing of the FRFs, proved to be efficient and reproducible, allowing the identification of subtle differences in the vibrational behavior of the samples. In addition to being a non-destructive method, modal analysis proved to be a sensitive and technically adequate approach to evaluate properties related to the stiffness of concrete, and can complement traditional tests used in technological control.

It is concluded, therefore, that experimental modal analysis is a robust tool for dynamic characterization of concrete, enabling the differentiation between resistance classes through the identification of their natural frequencies and the shape of their spectral responses. The results obtained reinforce the potential of this technique for applications in quality control, structural monitoring and advanced studies on the dynamic performance of cementitious materials.

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